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THE COST OF WATER TREATMENT BY COAGULATION, SEDIMENTATION, AND RAPID SAND FILTRATION. PART I

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THE COST OF WATER TREATMENT

by

COAGULATION, SEDIMENTATION
and
RAPID SAND FILTRATION

Part 1 of a Report

for

U. S. PUBLIC HEALTH SERVICE
Division of Water Supply and Pollution Control
Technical Services Branch
Under Contract No. PH 86-65-120

By
LOUIS KOENIG RESEARCH
San Antonio, Texas

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CHAPTER 1

INTRODUCTION

1-A ADMINISTRATIVE

This study on the costs of water treatment was initiated in discussions between Louis Koenig and personnel of the Technical Services Branch, Division of Water Supply and Pollution Control, USPHS in the spring of 1965 which resulted in a proposal entitled "Cost of Municipal Water Treatment" submitted in April, 1965. Contract No. PH 86-65-120 dated June 23, 1965 was negotiated covering the anticipated work. This report, Part 1 of a two part report, is the final report on that contract and covers all of the work with the exception of the effect of raw water quality on cost. During the course of the contract it was agreed to utilize techniques developed and in use by the PHS for multi-variate regression analysis using electronic computers in order to assess the effect of quality parameters on cost. This portion of the data, the mathematical analysis details, and the conclusions therefrom will be incorporated in Part 2 of the report under a subsequent arrangement.

The present work was originally considered as a pilot study to see what kinds of data were available, to what extent they might be utilized with accuracy, and what general conclusions might be drawn. Concurrently the Public Health Service has underway a study of the effect of raw water quality on treatment cost in a single plant which provides data in much greater detail than was obtainable from the random plants interviewed in this study. PHS has also conducted a separate study assessing the effect of raw water quality parameters on chemicals cost in 14 plants. All three of these related projects as well as others of similar nature are part of the effort to achieve a better understanding of the economics of water treatment in order to obtain the greatest public benefit in the use of the national materials and resources.

The assistance of the USPHS staff, James Coulter, Assistant Chief, Technical Services Branch, George Burke and William Pisano, Water Quality Criteria and Practice Section, Technical Services Branch, and Edwin L. Johnson, Economics Section, in planning the project and guiding the work is gratefully acknowledged.

1-B OBJECTIVES AND PURPOSES

We may differentiate between the objectives and the purposes of the study by defining objectives as the types of data and information to be developed out of the study, and the purposes as the uses to which this information is to be put.

The objectives of the study were:

To determine which elements, differentiable from the available plant data, make up the cost of water treatment.

To determine the relative magnitude of the contribution of each differentiable element.

To determine the unit consumptions or unit utilizations and the pertinent design factors and operating ratios for the plants studied. By unit utilizations or consumptions is meant the magnitude of the consumable items and certain other items per million gallons of water treated -- for example the man hours per million gallons, the pounds of alum per million gallons, the KWH energy per million gallons, etc. By design factors and operating ratios are meant those ratios of one plant datum to another which describe the design and operation of the plant -- for example sedimentation detention time, filter rate, percent of backwash water, etc.

To determine the unit investment and unit prices paid for materials and services.

To obtain the unit costs of selected cost elements, i.e. their contribution to the total cost of treatment. These are generally a product of a unit price and a unit consumption -- for example $/man hour x man hours/mg = $/mg for manpower.

To determine the distributions of these operating ratios, design factors, unit prices, unit consumptions and unit costs among all plants in the study.

To determine the effect of plant size on certain of these ratios such as unit prices, unit investment etc.

To determine the effect of climatic, geographical or administrative factors on certain of these ratios. As an example of a climatic factor it was an objective to determine whether some measure of climate dictated the covering and housing of basins and filters with a presumable effect on cost. As an example of an administrative factor it was an objective to determine whether the standards for water treatment plant construction set by the various state regulatory agencies introduced the differences among plants in various jurisdictions.

To determine the effect that water quality parameters have on the components of water treatment costs, on the total cost of water treatment and on the various operating ratios.

As distinguished from the objectives the purposes of the study included the following:

To provide plant management with data on the performance characteristics of other plants similar to their own so that they could assess in which elements their own plants were outstanding, so that they might seek and assign reasons for such outstanding characteristics, and so that if desired they might seek to apply remedial measures if they thought an improvement in some element was possible.

To provide administrators, engineers, and public officials concerned with the construction of particular future water treatment plants with information which would allow them to assess the general level of costs to be anticipated, prior to a detailed engineering determination of an estimated cost; for their guidance in making preliminary decisions concerning future plants; and for their use in assessing in general the relative level of bid prices submitted for actual construction and operation of the particular plant.

To provide for water resource planners and economists information on the ranges of expected water treatment costs useful to them in wholesale studies of water resource economics.

To provide data useful in cost-benefit analyses in which the general objective is the optimization of pollution control measures against other water uses, specifically in this study water treatment costs. The objective of determining the influence of raw water quality on treatment costs was particularly directed to this purpose.

To obtain at least some preliminary data bearing on the question: Is there some reasonable probability that water treatment costs could be reduced over present practice in design and operation, by the application of modern process optimization techniques?.

To assess the adequacy of the data available in typical water treatment plants for application to the above objectives and to provide data for preliminary estimates of the cost of performing such studies for a larger sample -- this study being considered as a pilot study toward that larger study.

To assess the degree of cooperation to be expected from technical and financial management in similar interview campaigns.

CHAPTER 2

SUMMARY

For 30 water treatment plants using coagulation, sedimentation and rapid sand filtration detailed cost engineering studies were made by collecting design, operating and economic data in actual field interviews. The sample comprised plants in two capability bands, the smaller in the region of 0.5 mgd and the larger surrounding 8.0 mgd. With tolerance for certain compromises involving an adequate size of sample the smaller size plant represents the median size treatment plant of this type among all such plants in the nation, and the larger size plant represents the median size in amount of water produced among community water supplies in the nation.

For each plant the data were reduced and expressed in a series of some 80 separate items in five categories as follows. (The parenthesis gives a single example from each category).

Design factors (design detention sedimentation basin, min.)
Unit prices (operator and maintenance labor, $/hr)
Production factors (average filter rate, gpm/sf)
Unit consumptions (manpower, hours/mg)
Unit costs (pumping energy, ¢/mg)

Tables 8-13 contain the basic reduced data for each plant.

The distributions of the values of each of these 80 items, (some of them separated by large and small plants) are provided in a series of Tables 14-19, which show the 10 percentile, the 50 percentile and the 90 percentile levels of each value. The 50 percentile value is the best measure of current practice and from the distributions each plant manager can determine where his plant stands relative to similar plants with respect to each item. It is of course impossible to summarize even this summarization of the data, but some of the unexpected relations seem worth mentioning.

There is a considerable spread in design manpower, man hours/mg of design capability. For the small plants most of this spread comes about in the difference between automatic plants capable of unattended operation and the non-automatic plants which must have an operator in attendance while they are producing. The large plants however are all attended 24 hours per day but the number of men per shift shows considerable variance. Among these plants, having the same type of equipment, the same type of operation and the same size, a number operate with about 1.5 men per shift while others utilize up to more than 4 men per shift.

In unit prices labor is typically lower in small plants representing no doubt the labor market conditions in the smaller communities. High labor prices are associated with automatic plants; which is the cause and which is the effect was not determinable from the data.

Among production factors the utilization factor (ratio of actual production to design capability) was about 0.4 for the smaller plants and 0.6 for the larger.

A new term is introduced replacing the conventional "hours of filter run". It is termed "rational filter run" and the units are kilogallons of water filtered per square foot backwashed. The median for this is 4.75, which indicates that in the median plant it was possible to filter 4750 gallons through each square foot of filter before it was necessary to backwash.

Under unit consumptions, it was shown that the labor requirement for a water treatment plant is very much less than that for a chemical processing plant of the same size and complexity in process steps.

The unit pumping energy for raw water pumping, for finished water pumping, and for total pumping is greater in small plants than in large plants, in the median the differences being of the order of 25% for total pumping energy and 40-50% for raw water and finished water energy separately. The small amount of data developed on total dynamic head and on pumping efficiencies suggest that the smaller plants tend to have higher TDH and lower pumping efficiency than the larger plants. Such pumping efficiencies as were obtainable suggest that conventional wire-to-water efficiencies of 65-75% frequently used in economic computations might well be revised to about 55% to represent average actual conditions.

Investment costs were adjusted by a specially developed cost index to 1964 costs. For the correlation of investment costs with design capability they were also de-regionalized to represent national average costs. While not demonstrable from the present study (containing only two design capabilities) it is known from other studies that in this size region investment costs are correlatable with design capability by a log-log linear line. This regression line from the data of the present study has the equation:

$$\text{unit investment, } ¢/\text{gpd} = 30.7 \times Q_d^{-0.323}$$

where: Q_d = design capability, mgd. The correlation coefficient is 0.768 and this is significant at the one in a thousand level.

It is to be noted that, as has been found in the author's studies of many types of processes, the distribution of economic and operating factors is generally not normal but is log-normal. This calls for special treatment in the statistical analysis and also in some applications of the data which on the incorrect assumption of normal distribution are commonly overlooked.

About 60% of the variance in the raw investment cost data is removed by the correlation with design capability. Explorations were undertaken to determine if the remaining dispersion could be ascribed to certain types of construction or equipment or to the requirements of climate. The available data were really not adequate for a complete analysis and the statements here are to be taken only as leads toward further study of the question. Explored were whether the equipment was housed or not, whether the plant had suspended solids contact clarifiers rather than conventional sedimentation basins and whether the plant was capable of automatic non-attended operation. The housing of equipment would bring about a cost differential much less than the general dispersion in

investment costs. This statement does not apply to the housing of sedimentation basins, which would result in an appreciable increase in investment. It is believed that this may be the major reason for the high incidence of suspended solids contact clarifiers in place of conventional sedimentation basins in the northern climates. This statement applies only to the sample, since the sample was not designed as a means of projecting the incidence of clarifiers in the universe of plants. As a whole the data are not inconsistent with a hypothesis that clarifiers reduce investment costs while unattended operation capability increases it but more data would be required to statistically test this hypothesis.

If the modal plant type is taken as having filters housed and sedimentation basins in the open then plants in the southern climates tend to depart from this mode by having the filters in the open and the plants in northern climates depart by having the sedimentation basins and clarifiers housed or covered. Nevertheless the dispersion of investment cost ascribable to the requirements of climate is very small compared to the dispersion of investment costs arising from other non-specified causes.

Some data were obtained on the percentage contributions of raw water and finished water pumping stations to the total cost. The treatment plant itself will represent 55-90% of the total cost with a median around 80%. The remaining 20% comprises the pump stations in various proportions, in the median the finished water pump station contributing twice as much as the raw water pump station.

As to contribution to the investment of various equipment elements the contributions of the filters, sedimentation basins and clarifiers are comparatively small, averaging about 18% of the total investment for filters and 14% for sedimentation basins or clarifiers. A major item in the cost of installation is the building, averaging around 44% of the total investment. It is worthwhile to further investigate the proposition that if one wishes to reduce the cost of treatment plants one should not spend too much effort trying to reduce the cost of filters, sedimentation basins, clarifiers and pump stations before he had more thoroughly investigated whether it is not possible to reduce the cost of housing the installation.

An exploration of the relative contribution of individual cost elements to total treatment cost, ¢/kilogallon, was made by considering a hypothetical plant which had the median unit cost for each component. The major contribution to total cost is made by the investment, it being of the order of 40-50% of costs depending on the utilization factor. The next major item is manpower contributing 27-37% in plants at typical utilization factors. Ranking well below the first two is energy with about 8-13% contribution. The total contribution of these three major items makes up nearly 90% of the cost. Chemicals contribute 4-6% and heating in northern climates and maintenance and repair each about 2%.

From these figures it is obvious that no major reductions in treatment costs, especially at actual utilization factors can be expected via the components chemicals, maintenance and repair, miscellaneous or heating. To reduce treatment costs the primary candidate for attention should be investment and the secondary candidate manpower.

The extent by which total treatment costs might reasonably be expected to be reduced was shown by analyzing the contribution of cost components in plants in which the

two major items, investment and manpower, had been reduced from the median level to the level achieved by the best 10 percentile of the plants. These two items still remain the major components of total cost and the results show that it is unreasonable under present practice (i.e. by managerial or design talent) to expect cost reductions of much more than one-quarter and one-third for small and large plants resp., as compared to the present median costs. This is not to say that every effort should not be expended to achieve these ideal performances in investment and manpower. On the other hand the economies to be achieved by pursuing lower prices for chemicals, lower maintenance costs or lower heating costs will not make a very big dent in the cost of water treatment.

If a proposed plant is faced with construction costs placing the investment in the 90th percentile level then a reduction in investment bringing it down only as far as the 85th-88th percentile would achieve a saving equivalent to eliminating the cost of chemicals entirely. If the plant has already been constructed the manager is saddled with the investment cost and it is outside his present sphere of responsibility. However, then a similar statement could be made about the importance of reducing manpower as compared with reducing chemicals, maintenance, etc. It is clear that during the planning and early operation period every effort should be made to reduce unit manpower since once an excessive manpower has become established by virtue of design or tradition it is exceedingly difficult to reduce it.

Typical water balances were developed showing that median recoveries from raw water intake of the order of 95% for sedimentation basin plants and 93% for suspended solids contact clarifier plants can be expected, less an unknown amount for plant leaks. Most of the plants in the study did not measure the plant service water; however two plants that did measure it showed a quite high percentage of such usage. There is no reason to believe that this is not the general case and attention should be directed to it. A great deal is made of the backwash percentage, this figure being computed by practically every plant and called for by almost all State Health Department reports. Yet plant service water representing a loss of not much less than the backwash is not even measured by most plants.

A special study was made of the cost of backwashing whereby it was shown that of the total cost of backwashing the cost of the water used makes up about 90%. A cost engineering analysis of the backwashing operation shows that the saving in cost continues to increase as the hours of filter run increases, but that for each plant there is a point of diminishing returns, that is an hours of filter run beyond which the incremental saving achieved is very small and continually diminishing. For median plants this point of diminishing returns is about 40 hours. This hours of diminishing returns depends primarily upon the amount of water used per backwash, the median being about 100 gallons per square foot; the higher this figure the higher will be the hours of diminishing returns.

In absolute units, ¢/kilogallon the cost of backwashing depends not only on the filter run achieved but also on the total cost of treatment, representing the value of the backwash water used. This means that from the standpoint of unit costs (not percentage savings) it is more important to seek long filter runs in small plants than in large ones.

A study was undertaken on the cost of cleaning sedimentation basins primarily directed toward the economics of mechanical sludge removal. The cost of cleaning sedimentation basins represents only about 0.5% of total treatment cost, something of the order of 0.1¢/kilogallon of raw water. Mechanical sludge removal eliminates most of

this cleaning cost and in addition allows a reduction of about 20% in the size of the sedimentation basin. Unfortunately the percentage water loss in mechanical sludge removal was not obtainable from the data but if it is the same as the water loss in suspended solids contact clarifiers then in median plants there is no economy in mechanical sludge removal over manual cleaning. This conclusion however depends on the intricate relationships among various factors in the alternative plants. If these factors are taken from the 10 or 90 percentile of the distributions so as to be most favorable for mechanical sludge removal then an investment in mechanical sludge removal would be justified up to the extent of something of the order of 6% of the total investment.

A graph is presented whereby the total unit costs of treatment in the median plant can be estimated for any design capability and any average production within the range of the data. Simple means are also provided whereby the corresponding cost for the 10 percentile and the 90 percentile plants can be estimated. Also a factor is provided whereby these most probable values can be adjusted to give the arithmetic average of a number of plants so that this figure may be used in computing the approximate total costs of a multiplicity of plants as in water resource planning.

CHAPTER 3

PROCEDURES

3-A CHOICE OF SAMPLE

Since the number of plants which could be interviewed within the project funding was limited it was essential to select a sample which would provide the maximum of information toward the purposes of the study. The results should be applicable to the main body of existing water treatment plants and interviews should not be wasted on plants representing only a small portion of the population.

Selection of Plant Type

The 1958 Inventory of Municipal Water Facilities showed the following breakdown by treatment plant types (1).

Rapid sand filtration		4110
2145	Purification only	
270	Purification and softening	
66	" and Fe and Mn removal	
36	" " " " " " and softening	
355	Softening only	
903	Fe and Mn removal only	
330	Fe and Mn removal and softening	
Chlorination		5364
Misc.		437
		9911

Another breakdown from the same inventory shows the number of plants using filters as follows:

Rapid sand	2387
Rapid anthrafilt	330
Slow sand	106
Pressure	667

The above data indicate that the plant type having the largest number of installations is that with chlorination. However, chlorination is a simple and inexpensive process both as to operating costs and investment costs and while the information would be of value in a comprehensive study it is obvious that attention rather should be directed to rapid sand purification. These are the type most common after chlorination alone and are the type that will be called for in the future to deal with increasing pollution of surface supplies. Furthermore, the major portion of these plants are those having purification only, i.e. not incorporating softening or Fe and Mn removal. By purification is meant the process of coagulation, clarification, and filtration. The data show that there are some purification plants which incorporate softening, or Fe and Mn removal. However, the number of these combination plants compared to purification only plants is small. Their inclusion in the study however, would complicate the costing since they involve additional equipment and additional processing beyond purification only. Accordingly the study was confined to plants in which the processing comprised coagulation, clarification and rapid sand filtration followed by disinfection.

In the 1963 Inventory of Municipal Water Facilities (2) plants of this type are coded as: P (for purification
FRS (filter rapid sand)

The codes PH, PI and PHI signify purification plants incorporating softening or Fe and Mn removal. A random sample study of 54 PFRS plants showed only two (3.7%) having any other type of filters with FRS (one zeolite, one slow sand). Thus it will be efficient to eliminate those PFRS plants having any other F type. However some plants are coded FR or FS. Both of these were taken to indicate rapid sand filters. Accordingly the class involved up to this point is: P (not PH, PI, or PHI)

and

FR, FS or FRS (not any other F type)

Within this major category there were analyzed a random sample of 212 plants according to the other components again seeking to eliminate those combinations of equipment or process types which represent only a small portion of the plants. The analysis is shown in Table 1.

As an illustration of its meaning and use, under Code C, chemicals for coagulation or softening, it may first be deduced that the listed plants used chemicals only for coagulation and not for softening since softening plants were excluded from the general class. The subcodes of C included were those which used aluminum compounds as the floc former but no other floc former at the same time. The soda ash and lime were considered to be alkalinity adjusters. In the general class (PFRS, PFR and PFS) 96.7% were plants of this C type. Thus only 3.3% of the potential sample is eliminated by excluding other coagulants. Since these latter would complicate the costing and analysis this is considered an efficient exclusion.

Under K, plants using chemicals for corrosion were excluded since it would be virtually impossible to separate out the cost of chemicals for corrosion control from the cost of chemicals for coagulation. 77% of the sample in the general class did not use chemicals for corrosion.

However, it developed during the interviews that many plants listed in the Inventory as not using chemicals for corrosion control actually were using them since many plants adjusted the lime or soda ash dosage according to the pH of the finished water in order to maintain $CaCO_3$ stability.

Under T, chemicals for taste and odor control, there were included plants having no taste and odor control and also those having control with activated carbon. The reason for this is that to have eliminated the carbon plants would have seriously reduced the percentage and furthermore taste and odor was one of the important water quality parameters hoped to be studied.

Plants which had the desired characteristics in all codes comprised the plants for which the study was designed and were designated plants of the B-type. While the fraction of plants in the general class having included subcodes is high for any one subcode a probability calculation shows that the fraction is not high for plants falling simultaneously in all included subcodes. The probability, computed from the fractions assuming independence of each characteristic, that a plant would have each of the desired characteristics simultaneously was only 0.19. This probability applied to the 212 plants in the sample predicts 41 plants will have all characteristics simultaneously. The number by actual count in the sample is 43 or a frequency of 0.20. In the 1958 Inventory there are about 2066 P-FRS,-FR,-FS type plants, so there should be about 419 B-type plants in that Inventory, and in the 1963 Inventory a little more than this.

TABLE 1

BREAKDOWN OF 212 PFRS, PFR, PFS PLANTS BY ADDITIONAL CODES

Code	Description	Original Class (B-Type)					Relaxed Class (R-Type)
		Included Subcodes	Description	Excluded Subcodes	% Having Selected Subcodes	Total % Having Included Subcodes	Included Subcodes
C	Chemicals for coagulation or softening	A, AS, AL, ASL	Alum but no other coagulant	O, T, I		96.7	Same
M	Mixing device and flocculation basin	B	Baffle only		26.7	62.6	Any M
		P, T	Single mechanical only		22.7		
		TPS	Proprietary		13.2		
S	Sedimentation	O, BO	Open, not mechanical		43.1	74.8	Any S
		C, CB	Closed		10.7		
		OM, MB, M, CM, MV	Mechanical		9.0		
		MTPS SV	Proprietary		12.0		
D	Disinfection	C	Chlorine	All others	84.0	84.0	Any D
K	Chemicals for Corrosion	No K		Any K		77.0	Any K
A	Aeration	No A		Any A		82.0	Same
N	Ammoniation	No N		Any N		89.0	Same
R	Recarbonation	No R		Any R		96.7	Same
T	Chemicals for taste and odor	No T	No T&O control	T	63.0	93.0	AnyT
		TC	Carbon	Any other T	30.0		
V	Fluoridation	V or No V	Yes or No	None		100.0	Same

The B-type was decided upon without the benefit of any actual interviews. During the course of the interviews it became apparent that some of the restrictions could have been relaxed without affecting the results. For example it became apparent that the nature of the mixing device had very little influence on investment cost or operation and therefore the original class might as well have included all mixing devices rather than the restricted ones indicated. After the first interview tour it was found desirable to increase the number in the potential sample in order to decrease the geographical distance between interview plants so that a more efficient interviewing schedule could be set up. This was accomplished by relaxing the restrictions as indicated by the last column in the Table. This type of plant was termed the R-type. A few of the interviews covered plants not actually within the R-type. This came about either through error in transcription, error in coding in the Municipal Water Facilities Inventory or changes in plant type since the 1963 Inventory.

Selection of Standard Q_d bands

The following designations and symbols are used in this report:

Q, mgd — Volume of raw water influent for a particular day.

$\bar{Q}$, mgd — Average raw water intake over a multi-day period.

Q_d mgd — Design capability (for raw water feed) of the plant operated at constant uninterrupted production rate.

$\bar{U}$, fraction — Utilization factor for a given period, $\bar{Q}$ period/Q_d

The relation between unit cost such as ¢/Kgal or unit investment such as ¢/gpd of capability and size of plant, Q_d has been studied by the authors for dozens of processes including those in the water and waste field. The relation is very similar in all fields and the best linear representation of it is a log-log straight line. It is quite likely that the best form for statistically studying the effect of water quality parameters on cost will be of an arithmetic (rather than a logarithmic type). Therefore to include Q_d, an expected log-log relation along with the other parameters in a multi-variate regression analysis would very much complicate such an analysis. Accordingly Q_d was eliminated from the multivariate analysis by selecting for interview plants of sizes that grouped themselves relatively closely about certain standardized Q_d's. With only 40 data points at the most with which to analyze the effect of design water quality on investment cost it was believed that only two such standard Q_d's could be permitted.

Obviously some tolerance around the two selected Q_d's must be allowed in order to provide a sufficient sample for interview. The positionof the standard Q_d's with respect to each other must be far enough apart in log cycles of Q_d to fix a reasonable portion of the total cost-Q_d curve. Thirdly, the sizes selected should bear some reasonable relation to the sizes of plants actually in existence. As an example of the last -- if one attempted an extreme log cycle spread in the standard Q_d's it would be found that below the lower Q_d and above the upper Q_d lie only a very few establishments or a very small percentage of the total water produced. The bands then would be representative of only a minor portion of the total existing plants.

To provide data for rational decision there was produced a frequency distribution of the sample of 43 B-type plants by Q_d. Selected coordinates from this sample B distribution are shown in Table 2.

TABLE 2

Distribution of Plants

from sample of 43 B-type plants

Percentile of number of B-type plants having greater Q_d's	Q_d mgd
10	4.8
50	0.6
90	0.15

This shows that the median B-type plant judged from the sample of 43 has a Q_d of about 0.6 mgd.

Data are not available to determine the corresponding median in terms of water produced (as distinct from number of plants) but Table 3 shows this distribution for the total population of U. S. waterworks. The distribution actually is based on $\bar{Q}$ since the distribution by Q_d is not available. The Table assumes that each plant is operating at a 50% utilization factor ($\bar{Q}/Q_d$). This indicates that 50% of the U. S. municipal water is produced in waterworks having a Q_d greater than 48 mgd.

TABLE 3

Distribution of water produced
from 18,000 U. S. Water Works

Percentile of total $\bar{Q}$ produced in larger plants	$\bar{Q}$ mgd	Q_d *
10	810	1620
50	24	48
90	.5	1.0

* assuming $\bar{Q}/Q_d = 0.5$

It would be desirable to arrange the two standard Q_d bands such that the lower of them centered on the median plant and the upper of them centered on the median amount of water produced. With this ideal attained it could be stated that of all possible bands of equal width the lower band is the one in which a single plant selected at random is most likely to fall. Of the upper band it could be stated that of all bands of equal width the selected band represents the capability from which a single gallon of municipal water chosen at random is most likely to fall. Stated in another way the lower band is the most representative of the plants and the upper band is the most representative of the water produced. It happens that an upper band centering around the proper Q_d contains too few plants of the B-type to constitute a sample. Various adjustments in band placement and band width were tried. The best compromise was the bands shown in Table 4.

TABLE 4
RANGES SELECTED

Q_d range mgd	Expected no. B-type plants	Expected % of B-type plants above range	% of U. S. water produced above range*	Actual no. in 1963 Inventory
0.3 - 0.50	67	56	95	78
3 - 13.0	18	3.6	63	36

* assuming $\bar{Q}/Q_d = 0.5$

The lower selected range lies only slightly below the median for the number of B-type plants, was expected on the basis of the sample to produce 67 B-type plants, and actually produced 78 when the 1963 Inventory was combed, entry by entry. The large size range is somewhat farther from the median of water produced in all U. S. plants, was expected to produce 18 such plants and actually produced 36. This indicates that the sample of 43 was deficient in representing plants of the larger sizes. But this has no effect on the adequacy of Table 2 since the deficiency lies above the 96th percentile while the purpose of Table 2 is centered on the 50th percentile.

Characteristics of the Class Population

The following discussion concerns the class of B-type plants. It is recognized that the sample finally interviewed contained some R-type plants. The characteristics of the R-type class would probably approximate those of the B-type class except that the number in the total population would be greater. The R-type proved economically identical with the B-type so the universe represented by the sample is greater than here indicated.

The plant sizes studied, measured by Q_d fell in two bands, the lower approximating the median size purification plant of this type, and the upper somewhat less closely approximating the municipal water system representing the median in amount of water produced. The ratio of the midpoints of the two bands was 20-fold. The national population of plants of this type comprises 78 in the lower size range and 36 in the upper.

Some statistical analyses describing the characteristics of these two national populations are as follows.

The rated capacity, Q_d, read from the 1963 Inventory, shows a strong tendency to cluster around round number values within each range such as around 6.0, and around 7.0., etc. but there is no tendency for any particular round number (specifically either at the high end or the low end of the range) to be favored.

The distribution by annual utilization factor, $\bar{U}_{1963}$, is log-normal and for the two bands has the characteristics shown in Table 5.

TABLE 5
DISTRIBUTION OF $\bar{U}$ IN POPULATION

Q_d range mgd	Number in Nation	Number in Distribution of $\bar{Q}/Q_d$	$\bar{U}_{1963} = \bar{Q}_{1963}/Q_d$ Percentile		
			10	50	90
0.3 - 0.50	78	61	.20	.38	.71
6 - 13.0	36	34	.26	.47	.83

Annual utilization factor is described as:

$$\bar{U}_{1963} = \bar{Q}_{1963}/Q_d$$

namely the ratio of the annual average flow to the design capability. The median utilization in 1963 of the design capability of these plants was 0.47 for the larger band and 0.38 for the smaller.

Attempted correlation of years of operation under the present Q_d (i.e. since the last major expansion of capability) against $\bar{U}_{1963}$ showed that there was no secular trend in the population. Some plants built 25 years ago or earlier are still operating with an annual $\bar{U}$ less than 0.3. On the other hand some plants built less than 10 years ago are already operating at an annual $\bar{U}$ greater than 0.9.

Some theoretical analyses were undertaken to develop the type of dispersion which would be expected in the annual $\bar{U}$ versus years of operation plots under two different design criteria, one in which the design was for a certain future year and the other in which it was for a certain amount of growth measured as a multiple of the initial year production. The dispersion of the actual points fell in between these two theoretical dispersions and the only conclusion that can be drawn is that neither one of these distinct practices predominates over the other in the actual population.

Table 6 shows the distribution of the national population by years of operation under the present Q_d.

TABLE 6

AGE DISTRIBUTION* OF POPULATION

Q_d range	No. in distn. of years of operation under present Q_d	Years of operation under present Q_d Percentile			
		10	50	90	Extreme
0.3 - 0.50	61	5	14	35	55
6 - 13.0	27	1.3	5.6	12	55

*The distribution closely approximates log-normal

The population in the small Q_d class is considerably older than that in the larger.

The geographical distribution of the population is not shown here in order to avoid disclosure of the identity of the individual plants. The plants are concentrated in the East, partly because the density of communities is greatest in the East, but also probably because the communities in the West are more likely to be served by ground water and thus not have the need for B-type plants.

3-B WATER TREATMENT PLANT CONSTRUCTION COST INDEXES

A number of historical construction cost indexes are available for waterworks properties. The index used in this study for water purification plants was developed from the design used by Orlob and Lindorf in their study of California water treatment costs (3). This index is computed from materials and labor prices obtainable in the Engineering News Record series of 20-Cities prices. The index has a fixed composition and thus does not take into account changes in labor productivity. This deficiency is judged not to be serious

for plants built after 1940. Orlob-Lindorf cost indexes were computed for each of the 20 regions for the years back to 1940.

Investment costs incurred prior to 1940 were adjusted to 1940 by the Engineering News Record (National) Building Cost Index, and from that base adjusted to 1964 National by the Orlob-Lindorf regional indexes.

3-C DATA COLLECTION

Letters were sent to the 114 plants in the national population, describing the purpose of the project and what was desired in the way of access and information. A stamped self-addressed envelope was enclosed for returning a short form indicating the general adequacy of the plant records plus a space for declining the interview. Only 24 replies were received and 10 of these were declining the interview. Nevertheless the interview tour was undertaken and it was found that the failure to receive or in a few cases to return the inquiry in no way affected the cooperation and hospitality shown by the plant and municipality personnel. Persons interviewed included treatment plant operators, chief operators, purification superintendents, water system managers, and city officials including managers, mayors, city clerks, treasurers, etc. For the most part the operating data was at the treatment plant while the financial and cost data was at the city office.

A 10-page check list illustrated as Appendix 1, was used for the interviewing and data recording. Not all of the check list was filled in for as the interviewing and data processing proceeded it was found permissible to omit some of the information. The check list was supplemented with sketches of the plant facilities including dimensions. In practically all cases it was found possible to greatly expand the original intention which was to collect data on production, chemical consumption, energy consumption and raw water quality parameters over only a few periods. It was found possible to obtain these data by monthly periods so that the pages of the check list dealing with these data were not used as such. In some cases monthly totals and averages were available from daily operating records with totals and averages already computed. In other cases the daily data were available on monthly sheets but not totaled or averaged. In that case the sheets were borrowed from the water department or from the State Health Department and were sent to the author's home office for totaling and averaging. In other cases where copies could not be released local labor was hired to perform the totaling and averaging. Sometimes it was possible to have reproductions made of the data sheets for processing at the home office. In some cases, fortunately few, only individual daily sheets were available and these were borrowed and processed at the home office.

As may be seen the check list contains a number of items designed to assess the accuracy and adequacy of the data, and also to obtain the operator's qualitative opinions on certain matters concerning the influence of water quality on operation. In addition the first order of business in each interview was to question the operator and superintendent about the source of each item entered on the daily or monthly data sheets. A record was made of exactly how each entry was obtained, from where the sample or measurement was taken, which other data entered into its computation and the actual method of computing the figure entered.

Despite these efforts it was found necessary in many cases, during the processing, to make additional inquiries by phone or letter in order to clarify aspects of the data. The number of permutations and combinations by which operators can contrive to make data mean something different from what it appears to mean seem to be without limit. While it is not possible to record here all the turns of the chase, the following discussion will illustrate the complexity behind what appears to be a quite simple datum, namely the amount of water treated.

This basic datum is demanded by all State Health Department reporting forms and most water department record forms make some effort at reporting it. First, one must determine just what is being measured. Some plants may report the raw water leaving their low lift pumps. One must inuqire concerning leaks and concerning the occasional practice of selling raw water to some industrial plant along the line. Others may report the raw water entering the plant. Very frequently amount of water treated means the amount of finished water pumped to the distribution system. When the backwash water is taken from the high line one must determine whether this finished water measuring point occurs before or after the backwash takeoff point. The sample applies to the takeoff point for plant service water for washing up, for lawn watering, etc. Whichever kind of water, raw or treated, is used for washing the sedimentation basins, one must determine the relation of the takeoff point to the metering point.

Once it has been determined what is being measured the next step is to determine how it is being measured. In some plants a totalizing meter is read daily or at the beginning of each shift. In others a flow meter is read periodically and integrated to give the daily flow. The data must be scrutinized for internal consistency in order to detect periods when the meters may have been reading incorrectly.

Some plants do not have meters. Some have calibrated the output of their pumps and compute the water volume by the time over which each pump is in operation. Pump hours may be taken from a recording chart. If it is, one must determine whether this chart is read to the hour, to the quarter hour, to the minute, etc. In some plants the only such record is the time of starting the pump in the morning and the time of shutting it down at night. This particularly occurs in the small plants which are not operated 24 hours per day. In that case it must be determined whether the pump is actually in continuous operation during the indicated period or whether there are shutdown periods during the daily operation. If so, the length of the average shut down periods must be estimated. In cases in which a calibration of a pump output or a butterfly valve setting is involved one must inquire when this calibration was performed, how and by whom, (usually by a consulting engineer or State Health Department representative). In some cases calibrations of flows etc. were performed in the couse of the interview in order to obtain information which would validate basic data in the records.

In addition to information obtained from the water facility itself further information in many cases was obtained by telephone or correspondence with the design engineer for the plant, the contractor who constructed the plant, retired plant operators and superintendents, and state, district, county or city Health Department engineers and records.

3-D DATA REDUCTION

The large amount of data collected as described above was processed to reduce it to a set of uniform units, to check internal consistency, and to eliminate those data elements believed to be inadequate for the intended analysis. The data so processed was compiled on large columnar sheets, one for each plant, and each divided into two parts. One part of the sheets contained the monthly data on water quality, unit consumptions, and other measures designed for the multi-variate regression analysis. The other portion contained the single valued ratios and measures applying to the plant itself and to a multi-month period providing information on the average performance of the plant in a typical recent period.

The second of these portions is described and tabulated in this Part 1 of the report. In the Part 2 of the report to be issued subsequently there will be described the data relating to the monthly values.

3-D-1 IDENTIFICATION AND DESCRIPTION AND DESIGN FACTORS

Serial identification number
Alphabetic description code

Design capability, Q_d, mgd
Mixing basin detention, min
Flocculation, basin detention, min
Sedimentation basin or clarifier
- Detention, min.
- Surface loading, gpm/sf
- Average transport rate, fpm
- Sludge drain %
- Basins housed or covered

Filter rate, gpm/sf
Filters housed or covered
Manpower, man hrs/mg
Days 32° and below, days/yr

The serial identification number is a two-digit number used for identification of the plant and for collation of the punched cards.

The description code is an alphabetic code by which the plant equipment and processing is described in shorthand form. The code is modified from that used in the 1963 Inventory Municipal Water Facilities and is presented as Appendix II. Besides the additions to the IMWF code which are self explanatory the major change has been to separate the mixing tank from the flocculation basin.

The design capability is the raw water intake for which the plant is designed. This was obtained from the plant specifications. In all plants interviewed the controlling factor was the filter area rather than the raw water or finished water pumping capability. Where such a rated capability was not available it was computed using a 2.00 gpm/sf filter rate or in one case a 3.0 gpm/sf rate. This design capability represents the raw water intake if the plant were operated continuously 24 hours per day. When a plant has mechanical sludge removal by continuous or intermittent draining of the sludge the average raw water flow is greater than the water applied to the filters by the amount lost in draining the sludge. This amounts to only a few percent of the raw water and no adjustment was made for it in arriving at design capability for raw water.

The design mixing basin detention time was computed by dividing the volume of the mixing chamber by the design capability. The flocculation basin detention time was computed in the same way.

The sedimentation basin or clarifier design detention time was computed as above. The surface loading was computed by dividing the design capability by the horizontal area, i.e. the air-water interface, of the basin. Surface loading is thought by some to be of theoretical importance in sedimentation basin design.

The average design transport rate, in a conventional simple rectangular sedimentation basin was obtained by dividing the design capability by the cross sectional area transverse to the flow through the basin. This computation breaks down when the basin is circular and the flow is radial or when the basin is baffled. In that case the corresponding ratio is obtained by dividing the average distance travelled by a water particle by the detention time. The general relation applying to any shape is

$$\frac{\int_0^T \bar{v}\,\delta t}{\int_0^T \delta t} = \frac{\text{average travel distance}}{T}$$

where:

$\bar{v}$ = instantaneous velocity of the average particle
t = time
T = detention time

When the clarifier is a suspended solids upflow unit the transport rate is the upward velocity at the normal sludge surface.

Some suspended solids contact clarifiers have the chemicals added in the clarifier itself while others have a separate mixing chamber. The figure for sedimentation detention in suspended solids contact clarifiers includes the detention in the mixing chamber if external and in the mixing, flocculation, and sedimentation portions of the clarifier itself.

Sedimentation basins and filters are designated as housed when they are contained within occupied space in a building. They are designated as covered when they have a concrete or earth cover such that the space above and around the basins is not designed to be occupied by personnel.

The filter rate is computed by dividing the design capability by the total cross-sectional area of the filter media. This is the rate that would apply if the plant were operating at design capability using all filters. The filter rate is expressed in terms of raw water feed. Where there is a loss between the raw water intake and the filter surface as in sedimentation basins with sludge drainage, the actual filter rate in terms of water applied to the filter will be somewhat less than the design filter rate here computed.

The design manpower is computed by dividing the man hours required to operate the plant 24 hours per day at its design capability by that design capability. In all interviews it was found that when a plant is operated 24 hours per day the manpower used is independent of the actual production rate. Accordingly the design manpower for such plants is taken as the actual manpower being utilized. When a plant does not operate 24 hours per day it is found in most plants that the operator is in attendance only while the plant is operating. To obtain the design manpower in such cases the superintendent or operators or in some cases the design engineer were questioned as to the manpower that would be required if operation was required 24 hours per day.

The term "days 32° and below" indicates the average number of days per year in which the minimum daily temperature was 32°F or less. Desired was some climatological measure which might have a direct bearing on the necessity for housing or covering basins and filters. Of the available published data (e.g. ref. 4) this seemed to be that most likely to influence this construction. The averages are for the period 1921-1950 and in many cases the figures given in the Tables are estimated from two or three nearby reporting stations.

3-D-2 UNIT PRICES

Investment, ¢/gpd of Q_d
- Adjusted to 1964
- Deregionalized and adjusted to 1964
- " " " " " and to include RW pump station

Labor (incl. payroll extras)
- Supervisor $/hr
- Operators and maintenance, $/hr
- General labor, $/hr

Energy
- Electric ¢/KWH
- Oil (for heat) ¢/Kcf

Chemicals, ¢/lb
- Coagulant
  - Alum
  - Iron sulfate
- Coagulant Auxiliary
  - Clay
  - $CaCO_3$
  - Na_2SiO_3
  - $(NH_4)_2SO_4$
  - Wisprofloc
- Alkali
  - Type
  - ¢/lb. hydrated lime equiv.
- Disinfection
  - Chlorine
- Taste and Odor
  - Carbon
  - $KMnO_4$

The standard investment in the existing plant facilities (¢/gpd of raw water design capability) was computed by trending to 1964 and deregionalizing, with the Water Treatment Plant Construction Cost Index as described, each separate investment transaction. In a few cases information was lacking for minor elements of the existing plant, such as for a pump addition, a feeder addition, etc. In these cases the 1964 cost of the item was estimated from data in the author's files. In some cases it was not possible to separate out the investment in a long intake line or delivery line. The inclusion of a long pipeline might seriously affect the total cost and invalidate the comparability of the results. Accordingly when a raw water or finished water pipeline was involved the cost thereof was eliminated from the investment. Where the cost of the line was not differentiable in the data this was done by subtracting the length of line at a per mile 1964 cost estimated from the author's extensive studies on this subject.

The unit investment then covers the intake if it is a simple structure, the low lift pumping station if one exists, the treatment plant itself and the high lift pumping station incorporated therewith. It does not include conveyance lines for raw water or finished water nor booster stations on finished water lines or distribution lines.

Two investments for the existing plant adjusted to 1964 are given. One of these not deregionalized shows the 1964 cost of the plant in the region in which it is constructed. The second has been deregionalized to national average construction costs and shows what the unit investment in the existing plant would be at national average prices.

A third investment is also shown. A few plants did not have raw water pumping stations because they were able to use gravity flow. If an attempt should be made to correlate raw water quality parameters for example with unit investment these plants lacking raw water pumping stations would introduce an extraneous dispersion into the data which has no correlation whatsoever with raw water quality parameters, and is only a happenstance of the differences in elevations of source and plant. To provide the maximum of data on unit investment for correlation purposes an adjustment was made in the unit investment for these plants by using the extensive data in the author's files to estimate the costs of a raw water pumping station operating against a total dynamic head of 70 feet which was the average total dynamic head of the raw water pumping stations for which data were available. The firm wire horsepower was computed using a 0.75 wire-to-water efficiency and the firm wire horsepower so obtained was converted to installed horsepower by an appropriate firming factor.

The unit prices for labor are given as $/hr regardless of whether the actual compensation was per hour, per week or per month. The prices represent the wage scale in effect in mid-1965. The figures given include the payroll extras which are actual average sickness experience, employer FICA tax, workmen's compensation insurance, employer's contribution to hospitalization and other group insurance plans, employer's contribution to city or state retirement plans. Payroll extras do not include vacation and holidays. For the regular operator, for example, the vacation and holiday time and wage is included in the computation of the basic wage rate and during a vacation or holiday period the man hour application includes both the man who is off and the man who replaces him.

Unit prices for energy and chemicals, delivered, were obtained from recent invoices, usually in the period July-September 1965. The usage of the term hydrated lime equivalent is explained in 3-D-4 beyond.

3-D-3 PRODUCTION FACTORS (average for period)

- Average flow, $\bar{Q}$ mgd
- Utilization factor $\bar{U}$, fraction
- Average hrs/day plant operated
- Sedimentation detention, min.
- Filters
  - Average hours per day
  - Rate, gpm/sf
  - Run, Kgal/sf backwashed
- Average Raw water quality
  - Turbidity, ppm or J. U.
  - Temperature, ^{o}F
  - Alkalinity, total, ppm
  - Alkalinity phenolphthalen, ppm
  - Free CO_2, ppm
  - pH
  - Hardness, total, ppm $CaCO_3$
  - Hardness, non-carbonate, ppm $CaCO_3$
  - Total dissolved solids, ppm
  - Color, color units

Although data were collected for approximately 30 monthly periods, in most cases the production factors here shown are taken from the data for an integral number of years of production, i.e. two or one years. The purpose was to avoid biasing the averages by the inclusion of incomplete portions of annual cycles. Exceptions occurred when less than 12 months of data was available in which case the period includes all the available months. Also, if a period included 21-23 months the full number of months were taken rather than wasting the 9-11 months of the second year's data. Similarly a period of 32-35 months was taken when available.

The average flow $\bar{Q}$ is the raw water intake to the plant. In cases where the measurement was made for finished water rather than raw water the raw water figure was generated by adding to the finished water figure the amount of backwash, or clarifier sludge drainage, of sedimentation basin cleaning water, (a negligible amount) and where available the other plant service water. In most cases other plant service water is not measured or available and had to be neglected in the computations.

The utilization factor $\bar{U}$ is that for the nominal 24 month period included in the computations calculated as $\bar{Q}/Q_d$. The nominal 24 month period ended with some month between January and September 1965.

The average hours per day of plant operation is 24 hours minus any period of continuous shut down (not including intermittent shutdown as in automatic operation).

The detention in the sedimentation basin is the average detention for the data period.

The sedimentation detention time is that applying during the hours of operation of the plant as above defined. In other words it is the volume of the basin divided by the average gpm rate during the period when the plant is operated. The general formula applicable to plants with 24 hours per day operation and to plants with less than 24 hours per day operation is:

$$\frac{(\text{Volume of basin, gal}) \times (\text{Average hours per day plant operated}) \times 60}{10^6\ \bar{Q}}$$

According to this formula two identical plants operating at the same constant gpm rate, one for 24 hours per day and the other for 8 hours per day would shown the same sedimentation detention time. Obviously there would be some increase in effective sedimentation time for the plant in which the sedimentation basin stands quiescent for 16 hours each day. The first sedimentation basin volume applied to the filters on the following morning would have the advantage of 16 hours detention in addition to the nominally computed detention time. However the value of the last four hours in a sixteen hour detention period in reducing turbidity of the water applied to the filters is not as great as the value of the first four hours and the theories of sedimentation kinetics are too complicated for application in this study to make the correction. Thus it must be taken that in the present study for plants having a period of continuous shutdown, as overnight, the shutdown period has been considered nonexistent in computing the sedimentation time.

Filters utilization, average hours per day, is the average square ft hours per day divided by the total filters area, square feet. This number multiplied by 100/2[illegible] gives the percent time utilization for all the filters. The filter rate is the total gallons applied to the filters during the period divided by the summation of square foot minutes of filter operation. Where the filters were all of the same size the denominator is simply the filter area times the summation of filter minutes. Where the filters were not all of the same size the summation was conducted for each individual filter size.

The filter run is a new unit generated for the purposes of the project and entitled "rational filter run". Filter run, in hours, is a conventional unit used for measuring the required frequency of backwashing. However, plants differ among themselves in average filter rates and an individual plant may use a higher filter rate during periods of high production rate. Thus the conventional unit, filter run, hours, is not a measure useful in comparisons of the basic phenomenon. The comparable question is: how much water is it possible to filter before it is necessary to backwash? This figure is obtained by dividing the gallons put through a square foot in a period by the number of backwashes in the period or in a simpler concept dividing the total gallons produced by the summation of square feet backwashed.

The average water quality figures are the averages of the monthly averages for the period. In some cases monthly averages of certain water quality parameters could not be obtained because they were not measured in the plant. Where possible such missing data were filled in from occasional complete analyses so as to cover a complete annual cycle. However in most cases State Health Department files contained only one or two complete analyses. In some cases samples of the raw water were taken at the time of interview and were analyzed for the missing parameters at the next interviewed plant having the necessary equipment. In some cases, data on average raw water quality was obtained from a neighboring non-interviewed plant using the same source.

3-D-4 UNIT CONSUMPTIONS (average for period)

Manpower
- Total, man hrs/mg
- Cleaning basins, man hrs/mg

Energy
- Electric, total, KWH/Kgal
  - Raw water, KWH/Kgal
  - Finished water, KWH/Kgal
- Gas
  - Kcf/mg
- Oil
  - Gal/mg
- Backwash
  - KWH/mg raw water

Water
- Backwash, %

Sludge drain, %
Sedimentation basin cleaning, %
Other plant service, %
Chemicals
Alum, lbs/mg
etc.

The manpower utilization in the period was obtained by dividing the total man hours including supervision, maintenance and general labor by the total raw water intake. The manpower for cleaning the sedimentation basins included the plant labor involved as well as any outside labor hired or assigned particularly for the cleaning, and is not additive to the total manpower.

The electric energy unit consumptions include plant lighting and heating where the latter was by electricity. These energies are small compared to pumping energy and it is usually not possible to separate them out. Oil and gas consumption was primarily for heating.

The backwash energy is a figure computed per million gallons of raw water from the discharge pressure on the pump supplying the backwash water. This may be either pumping to storage, pumping directly for backwash, or withdrawing at highline pressure. It was necessary to make special measurements of this discharge pressure at a number of plants since it is not a regular datum. The computed energy was adjusted upward assuming a 70% wire-to-water efficiency to make it comparable with metered KWH figures. One plant had a KWH meter on the backwash pump.

The water consumption for backwash, for sludge drainage in mechanical sludge removal or suspended solids contact clarifier systems, and for other plant service is computed as a percent of the raw water intake. Data on other plant service water was ordinarily not available.

The chemicals consumption was obtained by summing the monthly consumptions. This figure was checked by comparing either total pounds of each chemical or total dollars for all chemicals against the purchases for a corresponding period in pounds or dollars obtained from the annual financial reports or in a number of cases obtained by auditing (in the accounting sense) the bookkeeper's invoices at the time of the interview. A beginning and ending inventory was not taken into account in this computation.

In the plants for which such data were available the discrepancies are as shown (pg 25), where a negative sign indicates that the purchases record showed less consumption than the plant operating data. It was decided beforehand to ignore differences of 10% or less and to use the plant records in those cases. Only two plants showed differences greater than this limit. The plant showing a 22% difference obtained the monthly consumption data by counting the number of bags of chemicals loaded into the feeder hoppers. There appeared to be very little chance of error in such a method of measurement, while on the other hand accounting department records are always subject to the inclusion of items not in the intended category since the allocation of expenditures according to a chart of accounts and definitions thereof is in many plants on a rudimentary plane. For that reason the monthly consumptions were accepted in that case.

Plant No.	Discrepancy in total chemicals costs, % of purchases
1	-6
4	10
7	-22
9	-10
14	0
17	-9
18	-2
19	6
21	-6
24	0
26	1
27	52
29	-1

In the plant showing a 52% difference, the chlorine consumption was known accurately from the cylinder changes and therefore was subtracted from the total purchases, yielding the invoiced cost of alum. The plant consumption of alum, known to be but an approximation, was adjusted proportionally to give an alum consumption equivalent to the invoiced cost residual, using the known unit price for alum.

In the interviewed plants a number of different chemicals are used for adjusting alkalinity and pH for the coagulation reaction and also incidentally to adjust pH for corrosion control in the finished water. In their alkalizing effect these chemicals are interchangeable according to their alkali content. The most frequent use is of hydrated lime. In order to make the data more comparable as well as to benefit the correlation process, dosages and unit prices of these alkalinity adjusting chemicals have been expressed in terms of hydrated lime equivalents. The following Table shows the conversion factors used to convert bulk chemical dosages or prices. Hydrated lime may have a CaO content in the range 63-73 percent and quick lime in the range of 75-99%. It was not possible to determine the exact CaO assay of each lime being used so the conversions are made on the assumption that the CaO assay is an average one for each. The true assays of soda ash, caustic soda and liquid caustic are much less subject to variance in commercial practice.

TABLE 7

HYDRATED LIME EQUIVALENTS FOR ALKALINITY ADJUSTING CHEMICALS

Bulk Chemical	Average Assay	Factor to Multiply	
		lbs. of bulk chemical to obtain lbs of 68% hydrated lime equivalent or ¢/lb of 68% h.l. equiv. to obtain ¢/lb of bulk chemical	¢/lb of bulk chemical to obtain ¢/lb of 68% h.l. equiv. or lbs of 68% h.l. equiv. to obtain lbs of bulk chemical
Hydrated lime	68%CaO	1.00	1.00
Quick lime	85% "	1.65	.605
Soda ash	58%Na_2O	1.02	.98
Caustic soda	76%Na_2O	1.34	.75
Liquid soda	50% NaOH	.68	1.54

3-D-5 UNIT COSTS (average for period

Chemicals, excluding fluoride
Energy, total
  Pumping
  Heating (on $\bar{Q}$)
    (on Q_d)
Manpower
  Manpower (on Q_d)
Maintenance and Repair
Misc. (on $\bar{Q}$)
  (on Q_d)
Total operating
Capital costs (7.787%) actual investment
Capital costs (on Q_d)
Total costs at actual prices
Total cost at Q_d, actual prices

The unit costs are expressed in as detailed a breakdown as is typically available from the plant and interview records. They are expressed per Kgal of raw water intake in the period. For comparative purposes certain of these are better expressed in terms of design capability.

These unit costs over the period will not correspond exactly with the costs determined from the accounting department records. For one thing accounting procedures sometimes use arbitrary allocations of shared costs; for example superintendent's salary might be allocated 60% to the sewage treatment plant and 40% to the water treatment plant whereas the supervisor actually spends only 10% of his time at the water treatment plant. The computations in this study utilized the actual unit consumptions as determined in the interview. Further, the unit costs given are computed by multiplying the average unit consumptions in the period by the mid-1965 unit prices. The unit costs thus are those that would be obtained if the unit prices during the period has been constant at their mid-1965 level. For example the unit cost incurred by the plant operator is that which would have occurred if his wage rate during the entire period had been the same as his wage rate at the end of the period.

The chemicals unit cost does not include the cost of fluoride chemicals. The cost of fluoridation is quite accurately computable from the amount of fluoride that must be added to reach the desired level in the finished water. Whether or not fluoridation is practiced of course is determined in the first place by raw water quality in the sense of fluoride content, but beyond this the incidence of fluoridation is highly erratic depending upon the local situation.

The capital costs are not those of debt retirement which occur in the actual cash flow of a plant. Instead they are based on a fixed annual cost of 7.783% of the plant investment adjusted to 1965. This figure is composed of 5.783% corresponding to repayment of the investment cost as a loan at 4% interest over 30 years in equal annual payments, plus 2% covering taxes and insurance. Most plants interviewed, being municipal plants, did not show costs for either taxes or plant insurance. However, if the plants were operated

as commercial enterprises such costs would be allocable to the plant operation. Inclusion of these costs is standard cost estimating practice in the process industries and will make the total costs more comparable between municipal and private operation.

Furthermore, such costs are social costs regardless of whether paid by the individual plant. The taxes represent a loss of tax revenue which comes about by investing the nation's resources in these tax free facilities as compared with a similar investment in private enterprise facilities.

Without arguing that the percentage allocated for insurance is a correct one a cost in lieu of insurance represents a total casualty experience over the nation averaged out over the plants involved. If the insurance allocation is a correct one the total cost in X plants over a 30 year period will approximate the cost of the casualty damage which statistically may be expected in Y plants out of X in the 30 year period. If desired the 2% for taxes and insurance may be eliminated from the costs by subtracting 2.00/7.783 times the listed capital costs from the listed costs.

Since maintenance, repair and replacement jobs do not occur regularly a special technique had to be used in order to obtain an average figure. An attempt was made to obtain MRR costs over a multi-year period considerably greater than the 30 month period covered by the rest of the data. The total MRR recorded in expenditures over that period were taken as an annual average and this annual average was allocated to the actual raw water intake during the actual study period. This corresponds to setting up a sinking fund for MRR expenses and charging it off as a uniform annual expense.

The miscellaneous costs include office and plant supplies, legal and accounting services, telephone and vehicles.

Finally there has been computed the total cost if the plant were operated at its design capability. The assumptions in this computation involved that unit costs of chemicals and energy remained the same, annual costs of manpower at Q_d were as determined in the interviews, annual miscellaneous costs remained the same as in the production period, and maintenance and repair annual costs increased as the 0.5 power of $\bar{U}$. This last assumption gives recognition to the likelihood that maintenance and repair would be greater if production were increased but that it would not increase directly proportional to production.

For some plants data were missing on unit costs for some of the major components thereof such as energy or investment. Lacking these major components it was not possible to use the total costs for these plants. For certain other plants some of the minor cost components, heating costs, miscellaneous, and MR were missing. As will later be shown these cost elements make only a very minor contribution to total costs. Therefore in order not to lose the data on the major cost elements already available some of the missing minor costs were filled in in the following manner.

Missing heating costs were filled in in the manner described in Chapter 5 under Unit costs.

Missing miscellaneous and MR costs were filled in by plotting the unit costs in these items for the plants where avilable against Q_d(log-log) and reading the trend line at the Q_d of the plant to be filled in. As has just previously been mentioned it was assumed that annual miscellaneous costs were independent of $\bar{U}$. The plot shows that if that assumption is correct unit miscellaneous costs are also independent of Q_d since there was no trend in the plot, the median value being 0.11¢/mg of Q_d.

For MR costs it was assumed that the trend line correctly represented the MR costs at the median $\bar{U}$ of approximately 0.47. Taking that to be the case the missing MR in ¢/Kgal of $\bar{Q}$ were computed by adjusting the trend line value by the square root of $\bar{U}$. This adjustment is acknowledged to be an approximate one even beyond the approximation of the 0.5 power. However, MR costs are but a small percentage of total costs and thus the total is not greatly affected by errors in MR costs.

None of the filled in data were used in the distributions of operating ratios. They were simply used as a means of arriving at a total cost.

CHAPTER 4

RESULTS

4-A LIMITATIONS OF THE BASIC DATA

The results of the data reduction are presented in a series of Tables in Section B of this Chapter. The present section discusses the nature of the basic data, particularly the limitations and deficiencies in it.

A question that will be obvious to the reader is why there are no finished water quality data. Certainly if one were studying softening plants for example, not only the raw water hardness but also the finished water hardness would be of importance in correlating the cost, since the chemical dosage would vary directly not with raw water hardness or finished water hardness but with the difference between them. However, for plants of the type studied in this report the finished water quality standards are so strict and the performance with respect to them is so uniformly high that in the parameters of interest there is very little variation from plant to plant or from month to month in their values in finished water. For components which are expected to be removed by the treatment process, that is for turbidity, for color, for taste and odor, and for coliform organisms the amounts remaining in the finished water are extremely low and in any case the intended goals in these measures are extremely low. Any deviations from these high standards of purity in the finished water are immediately recognized and corrective measures are applied. Accordingly in the monthly averages of these components there is very little variation month by month or plant by plant. Also they are all close to zero so that statistically the value of the raw water parameters cannot be distinguished from the change in parameter on treatment.

A real deficiency of the data is in the small number of raw water quality parameters which are regularly measured at water treatment plants. Of course it may be argued that these are the parameters by which the process is controlled and the operation monitored by regulatory agencies, and that therefore they can be expected to be the important parameters so far as operation is concerned. Beyond the common five parameters, temperature, turbidity, alkalinity, hardness and pH, one may wish for more frequent recording of taste and odor, color, dissolved oxygen, phenolphthalein alkalinity, noncarbonate hardness, total dissolved solids, free CO_2, BOD, COD, chlorine demand.

Even among the five common measurements there are glaring omissions, some plants lacking temperature, some turbidity, some hardness, etc. One wishes even more for some of these determinations because they are so simple. Raw water temperature for example could be measured daily with completely negligible increase of operator work load and no need for analytical training. A few of the interviewed plants made virtually no analyses of raw water. In one of the states covered there has been a recent law making mandatory the monthly reports to the State Health Department. Compliance on the part of management and operators was universally good in the plants interviewed despite the fact that some of the plants had to train their operators for the first time to perform the analyses.

The cost component of maintenance, repair and replacement is very insecure in the data. In most plants interviewed the labor for MRR is supplied by the regular operators and is not recorded in a separate account. This was so nearly universal in the sample

interviewed that in the few plants having separate maintenance personnel their payroll costs were included in labor in order to be consistent with the rest of the data. However, even for MRR materials and outside contract labor it was difficult to obtain a complete accounting. In part this comes about because major MRR jobs do not occur regularly. Very few of the interview plants had a separate accounting category for such expenses. It was actually very difficult to extricate such information, since historical MRR jobs proved to be easily overlooked in the course of normal interview questioning. Operators and managers had to be specifically asked such questions as: Have you ever changed the sand in the filters? Have you ever had to repair sedimentation basins? Have you ever replaced pumps or motors?, etc. Another difficulty, particularly in the smaller plants is the confusion of distribution system expenditures for MRR with treatment plant and pumping station expenditures. Even a very simple system of accounts could provide a treatment plant MRR account and a set of definitions governing it which could easily produce the desired data.

Surprisingly enough the investment in the plant seems to be a datum which is of little interest either to operating management or to the financial management in many of the communities interviewed. On the part of operating management this probably comes about because plant investment, post facto, is an item over which operating management has absolutely no control and which does not enter into the evaluation of their performance. Also the financial management of the plant, city clerks, etc. similarly have no control of the item, nor does it enter into their cash flow. The item of concern there is the debt retirement expense for the total system. In adequacy of the investment data, the interviewed plants ranged from a few having item by item tabulations showing invoice number, description, date and amount to communities in which none of the current personnel at the plant or at City Hall could locate or had ever seen a blueprint, a contract document, or any record even hearsay as to what the plant had cost. For the investment data actually obtained in this study the major deficiency was the occasional inability to distinguish whether the reported investment included certain extraneous items such as long pipelines, reservoirs, etc.

4-B TABULAR PRESENTATION

The tables in the remainder of this chapter present the reduced data for each plant in the study. Plants No. 11, 16 and 20 are missing because although interviewed they did not provide data suitable for the study.

Table 8 comprises the alphabetic descriptions of each plant according to the code in Appendix 2.

The remaining tables, 9-13, are in general self-explanatory and details are given in notes following each table.

In Table 10 the row titled "Percent Level of Deregionalized and Adjusted to 1964 Costs" is provided for plant managers who may wish to assess the percentile level of their unit investment as compared with the other plants in the sample. The percentile shows where the actual plant investment (national 1964) stands relative to the regression line investment. Thus Plant No. 1 is in the 38th percentile, i.e. better than median whereas Plant No. 4 is in the 91st percentile, i.e. more costly than median. The influence of the year of construction and of regional price levels has been removed from these percentile comparisons.

TABLE 8

Plant No.	DESCRIPTION
1	Qr Pl Ca Tcm Mt Gp Sm Frso Bp Dg Vs Pp
2	Qr Pl Sp Dg Cail Tc Mt Gpb Sb Frs1/2o Bp Dg Pp
3	Ql Cal Tc Mt Gp S Frs1/2o Bp Dg Vs Pp
4	Qr Pl Dg Cal Tc Mt Gb S Frso Bp Vt Pp
5	Qrl Pl Cas Ml Gp S Frs Bp Dg Pp
6	Qr Pl Dg Cal Ml Gp S Frs Bp Dg Pp
7	Qr Pl Cal Mt Gp S Frs Bp Dg Pp
8	Qs Dg Cal Mb Gb S Frs Bp Dg Pp
9	Qr Pl Dg Cal Td Mt Gp S Frs Bp Vt Pp
10	Qr Dg Cas Mt Gb S Frs Ba Dg Va Pp
12	Qr Cac Tm Mt Gbp (MTPS-SV)+S Frs Bp Dg Pp
13	Qr Pl Cal Cc Ml Gp S Frs Bl Dg Vs Pp
14	Ql Pl Dg Ca Tc (MPTS-SV)h Ml Frs Bp Pp
15	Qr Pl Dg Caso Mt (MPTS-SV)h Frs Bl Dg Pp
17	Qr Pl Ca Td Gp Sc Frs Bp Dg Pp
18	Ql Pl Ca(MTPS-SV) Fgsk Dg Pp
19	Qr Pl Dg Cao Tcd Me Gb Sb Frs1/2k Bp Dg Vs Pp
21	Ql Pl Dg Cil Mt Gp S Frso R Bp Pp
22	Ql Pl Calt Me (MTPS-SV)+S Frsk Bl Dg Vs Pp
23	Ql Pl Cal Tc Me Gb S Frs Bl Dg Pp
24	Ql Pl Cas Ml Gp Sb Fra Bl Dg Pp
25	Ql Pl Cal Tc Ml Gp S Frs Bl Dg Pp
26	Qs Cal Me Gb (MPTS-SV) Frs Bp Dg Pp
27	Qr Pl Ca Ml Gb S Frs Bl Dg Pp
28	Qr Pl Ccalt Tc Ml (MPTS-SV) R Frso Bp Dg Pp
29	Ql Pl Dg Cal Tc Mt Gp Sm Frso Bp Pp
30	Ql Calt Me S Frsk Bl Dg Vs Pp

TABLE 9 DESIGN FACTORS

Plant Number	1	2	3	4	5	6	7	8	9	10	12	13	14	15	17	18	19	21	22	23	24	25	26	27	28	29	30
Design Capability, Q_d, mgd	6.00	9.00	8.00	6.00	.500	.500	.500	.500	6.00	.300	12.00	8.00	.432	12.00	12.00	.300	8.00	7.50	6.81(1)	.576	.504	.504	.500	.486(1)	1.00	8.00	6.81(1)
Year of Last Major Addition to Plant	1959	1953	1950	1952	1953	1951	1960	1939	1957	1962	1958	1946	1947	1960	1961	1948	1946	1955	1955	1938	1930	1937	1965	1948	1964	1958	1955
Mixing Basin Detention, min.	1.3	5.0	.6	-	Ml (3)	Ml (3)	10.0	With Floc(3)	-	With Floc(3)	- (2)	Ml (3)	(2)	(2)	With Floc(3)	(2)	1.6	.7	(2)	-	Ml	Ml	(2)	1.1	(2)	2.4	.16
Flocculation Basin Detention, min.	30	30	40	65	51	52	43	20	57	16	17 (2)	10	(2)	(2)	23	(2)	33	51	(2)	7	22	29	(2)	142	(2)	39	
Sedimentation Basin or Clarifier Detention, min.	391	240	263	288	305	346	315	240	447	220	206 81(2)	212	67(2)	102(2)	202	47(2)	125	335	102(2)	327	249	283	229(2)	6960	280(2)	261	102
Surface Loading, gpm/sf	.651	.313	.333	.366	.329	.386	.273	.345	.225	.284	.290 (4)	.495	(2)	(2)	.778	(2)	.702	.321	(2)	.177	.326	.268	(2)	.011	(2)	.457	
Average Transport Rate, fpm	.102	.450	.586	.327	.190	.221	.144	.184	.278	.251	.580	1.16	-	16)(2)	.446	.262(2)	.925	.127	.600(2)	.566	.352	.340	.092(2)	.033	.161(2)	.427	.80
Clarifier Loading, gpm/sf													1.59	1.10		2.19			1.18				.491		.354		
Basins Housed or Covered (5)	o	o	o	o	o	o	o	o	o	o	o o	o	h	h	c	h	o	o	o	o	o	o	o	o	o	o	o
Filter Rate, gpm/sf	1.70	1.65	1.65	2.00	1.93	1.93	1.72	1.93	-	1.64	3.31	1.96	1.65	1.67	1.54	.075	1.93	1.94	2.00(1)	1.94	1.82	1.82	1.62	3.00(1)	1.49	1.95	2.00(1)
Filters Housed or Covered (5)	o	½o	½o	h	h	h	h	h	h	h	h	h	h	h	h	c	½c	o	c	h	h	h	h	h	o	o	c
Design Manpower Man hrs/mg	3.1	9.8	6.6	10.0	48.0	48.0	48.0	48.0	4.0	15.0	2.53	7.5	23.1	5.1	9.6	12.0	7.9	6.8	5.0	42.0	47.0	48.0	28.0	18.0	26.6	7.9	5.0
Days 32° and Below, days/yr.	11	17	48	33	81	63	63	90	37	65	94	100	148	144	144	144	144	11	65	65	83	73	70	70	66	59	65

NOTES:

(1) Based on an arbitrary design filter rate as shown.
(2) Suspended solids contact clarifier.
(3) Ml signifies mixing basins detention could not be computed because mixing is done in the line. "With floc" indicates mixing basin not seperatable from floculation basin and floculation detention includes both.
(4) This plant operates sedimentation basins and a clarifier in parallel. Data applicable to the clarifier are shown in the right hand column. Certain dimensions of the clarifier were not available.
(5) Housed, covered, open.

TABLE 10 UNIT PRICES

INVESTMENT, ¢/gpd of Q_d																											
Adjusted to 1964	15.1	-	16.0	34.5(1)	-	32.2(1)	48.6	39.0	-	65.3	5.6	10.4	54.9	18.0(1)	-	30.1	11.0	22.5	12.5	-	21.8	29.0	28.4	37.6	24.8	20.7	
Deregionalized & Adjusted to 1964	16.6	-	17.3	37.3	-	32.2	48.6	42.2	-	63.7	5.5	10.1	47.0	17.7	-	29.5	13.7	24.6	13.7	-	23.8	30.0	31.0	41.2	27.1	22.6	
Deregionalized, Adjusted to 1964 and to include RW pump station	16.6	-	17.8	37.3	-	32.2	48.6	46.0	-	70.0	5.5	10.1	47.0	17.7	15.0(2)	29.5	13.7	24.6	14.2	-	23.8	30.0	34.8	41.2	27.1	22.6	
% Level of Deregionalized & Adjusted to 1964 Cost	38	-	49	91	-	31	72	58	-	80	2	5	63	61	-	10	30	76	28	-	10	25	28	55	38	70	
LABOR																											
Supervisor, $/hr.	3.04	3.99	3.72	3.14	1.91	-	-	-	2.31	-	5.50	3.03	2.70	11.10(3)	4.70	3.08	3.32	4.47	1.91	3.93	1.51	-	-	-	1.93	3.74	1.91
Operator and Maintenance, $/hr.	2.05	2.01	1.79	2.05	1.62	1.24	1.63	1.55	2.26	2.03	3.38	2.04	1.63	3.19	2.04	2.62	3.05	3.14	1.70	3.93	1.38	1.55	1.72	1.72	1.70	2.16	1.70
General Labor, $/hr.	1.54	1.17	1.19	1.24	-	-	-	-	-	-	-	-	-	-	2.23	2.15	-	2.07	-	-	-	-	-	-	1.54	1.92	-
ENERGY																											
Electric, ¢/KWH	.92	.77	1.71	1.00	1.40	1.40	1.00	2.00	1.04	2.00	1.00	1.30	1.90	.77	.69	2.00	.91	.88	.70	1.33	-	-	1.20	1.20	1.04	.91	.70
Oil (for heat) ¢/gal.	-	-	-	-	-	-	-	-	-	-	-	-	15	9.6	10.5	16.9	9.9	-	-	-	-	-	-	-	-	-	-
Gas (for heat) ¢/Kcf	-	-	33.3	-	-	-	-	-	-	-	-	-	-	705(4)	-	-	-	76	-	-	-	-	-	-	30	47	-
CHEMICALS, ¢/lb																											
Coagulant																											
Alum	2.76	2.61	2.51	2.43	3.40	3.78	3.55	4.92	2.48	4.10	4.79	2.58	-	2.56	2.68	4.1	2.37	-	2.92	3.25	4.1	-	4.00	4.00	3.35	2.34	2.92
Iron Sulfate	2.60	1.81	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2.60	-	-	-	-	-	-	-	-	-
Coagulant Auxiliary																											
Clay							3.5																				
$CaCO_3$														1.33													
Na_2SiO_3																			2.92								
$(NH_4)_2SO_4$																									5.00		
Wisprofloc																									4.35		
Alkali																	27.5										
¢/lb Hydrated Lime Eqiv.	.88	1.20	.78	1.19	2.90	.33	1.5	1.65	1.50	3.33	4.55	1.1	-	-	-	-	-	.54	1.27	1.70	3.8	-	3.50	3.50	.80	1.22	1.27
Type	h	h	q	h	s	h	h	h	h	s	c	h	none	none	none	none	none	q	h	h	s	h	h	h	h	h	h
Disinfection																											
Chlorine	3.9	6.5	6.5	9.6	8.7	9.0	9.0	12.7	4.7	13	3.70	7.0	17.5	5.4	7.9	12.5	5.6	4.9	8.2	13.5	12.5	-	13.5	13.5	13.5	4.8	8.2
Taste and Odor																											
Carbon	9.6	-	-	12.5	-	-	-	-	-	12	-	10.0	-	-	-	-	11.6	7.5	14.7	12.2	-	-	-	-	-	13.6	14.7
$KMnO_4$	36										32							40									
$NaClO_2$															70		70										

NOTES:

(1) The cost of a pipeline of length to constitute an appreciable fraction of plant plus pipeline cost was estimated from author's data and removed from total cost.
(2) A raw water pump station exists but costs for it were not obtainable. Quantity shown is for cost of plant plus pump station estimated.
(3) Plant at present operating without a supervisor, but this role is filled by a consultant. The rate shown is the consultant's rate.
(4) Plant uses LPG and price is per liquid cubic foot.

TABLE II PRODUCTION FACTORS

(AVERAGE FOR PERIOD)

Plant Number	1	2	3	4	5	6	7	8	9	10	12	13	14	15	17	18	19	21	22	23	24	25	26	27	28	29	30
Average Production, $\bar{Q}$ mgd	1.87	7.09	5.82	4.71	.166	.163	.342	.157	1.57	.070	11.3	1.87	.196	4.91	9.25	.169	5.66	8.87	2.11(1)	.129	.328	.127	.174	.440(2)	.297	5.29	3.51
Utilization Factor, $\bar{U}$, Fraction	.31	.79	.73	.79	.33	.33	.68	.31	.26	.26	.94	.47	.46	.41	.77	.56	.71	1.18	.31	.22	.65	.25	.35	.89	.30	.66	.52
Average Hrs./Day Plant Operated	24	24	24	24	8.1	8.7	17	7.7	15	24	24	16	24	23	24	24	24	24	24	24	15	11.5	18	15	8	24	24
Sedimentation Detention, min.	1255	305	656	367	309	382	327	240	1074	846	219	302	146	239	214	83	176	283	331	1460	239	538	494	4802	314	394	198
Filters																											
Utilization, Average hrs./day	9.9	24	24	24	8.1	8.7	17	7.7	15	6.2	24	16	11	23	20	24	15	24	21	17	15	11.5	7.4	15	8	24	21
Rate, gpm/sf	1.29	1.30	1.34	1.60	1.89	1.75	1.65	1.89	-	1.64	3.12	1.38	1.85	.81	1.46	.042	2.30	2.29	1.36	.61	1.90	.82	1.83	4.3	1.36	1.29	1.36
Run, Kgal/sf Backwashed	5.0	3.8	7.0	8.1	6.7	3.8	7.6	4.4	-	-	1.5	3.9	9.5	4.7	6.5	1.8	3.8	9.0	2.0	3.2	6.0	.7	.8	3.9	4.3	5.4	4.0
Average Raw Water Quality																											
Turbidity, ppm	68	250	5(4)	72	-	-	86	10(4)	27 (6)	5.3	44	25	10	5	13	26	15	7	10(3)	5.8	155(3)	23	7	(6) 6	50	36	10(3)
Temperature °F	63	62	62	64	-	-	60	53	64(5)	63	58	58	49	54	49(5)	49(5)	49	68	62	-	-	-	80	-	75	67	70
Alkalinity Total, ppm	129	86	16	20	15	133	142	9	17(6)	24(3)	46	101	97(5)	102	156	-	156(5)	133	161	-	78(6)	39	82	104	26	69	166
Alkalinity Phenolphthalein, ppm	0	-	8(3)	-	-	-	0(3)	-	0 (6)	-	-	-	-	-	-	-	-	-	3	0	0(6)	0(6)	-	6	0	-	1
Free Cl_2, ppm	-	2.8	12	5	-	0	1.8	5	-	-	-	-	1(4)	2.2	-	-	-	-	-	-	-	-	7.9	-	-	9	-
pH	7.8	7.7	7.3	6.8	6.9	8.1	7.6	6.8	6.9(6)	7.1	7.3	7.9	7.8	7.8	8.2	-	7.9	7.6	8.0	7.8	7.6(6)	-	7.5	7.6	6.1	7.2	7.9
Hardness, Total, ppm $CaCO_3$	180	119	12	32	-	149(3)	159	10	12.5(6)	-	63(3)	122	113(5)	121	91	-	91(5)	152	181	-	118	84(6)	68	111	146	25	84	185
Hardness, non-carbonate, ppm $CaCO_3$	-	-	-	-	-	9(3)	-	0(3)	0 (6)	-	-	-	-	-	-	-	-	-	14(3)	-	6(6)	20(6)	84	42	0(6)	-	14(3)
Total Dissolved Solids, ppm	-	160(4)	-	41(6)	-	152(3)	-	134(3)	43 (6)	-	135(3)	-	130(5)	190(4)	190(4)	190(4)	190(4)	-	216(3)	-	130(6)	145(6)	143	230	40(6)	-	216(3)
Color	-	0	-	14(6)	-	7(3)	25(3)	5	10 (4)	38	33	-	9.8(4)	-	-	-	-	-	10(3)	-	350(6)	10(6)	15	5	149	-	10(3)

NOTES:

(1) Does not include that portion of the supply which comes from well water, except chlorine unit consumption based on total raw water. This plant has been operated in two different manners with the change over in March 1965. The two methods of operation are described as Plant No. 22 prior to 3/65 and No. 30 after 3/65.

(2) Production estimated from average production in first month during which distribution system was metered.

(3) From 2, 3, or 4 spot analyses in separate months during the data period. (Similar cases from a single spot analysis identified as Note 6.)

(4) Average data from sources other than the interview campaign. Period of average may not cover the data period and sampling location may not be precisely at intake.

(5) Data from a nearby plant using the same source.

(6) Data from a single spot analysis.

TABLE 12 Unit Consumptions

Plant Number	1	2	3	4	5	6	7	8	9	10	12	13	14	15	17	18	19	21	22	23	24	25	26	27	28	29	30
MANPOWER																											
Total, Man Hrs./mg	6.7	12.7	9.0	12.7	49	49	79	76	7.3	58	2.7	16	51	12.5	12.5	21	11	5.8	16	186	46	94	33	13	34	12	9.8
Cleaning Basins, Man Hrs./mg	0	.159	.049	.020	.132	.504	-	-	.035	.211	.014	.211			.004		.036	.005		.936	.600	.650		.300		.100	.032
ENERGY																											
Electric, Total, KWH/Kgal	1.73(1)	2.46	.33(3)	2.04	2.33	2.5(5)	3.25	2.15	3.27	2.39	1.42	1.32	2.37	2.32	1.41	1.60	.82	3.03	2.89	-	-	-	3.60	1.22	2.78	1.77	1.65
RW, KWH/Kgal	-	-	-	1.26	.94	-	1.29	-	-	-	-	-	-	.41	.70	-	-	-	-	-	-	-	-	-	1.11	.82	-
FW, KWH/Kgal	-	-	-	.78	1.39	-	1.96	-	-	-	-	-	-	1.91	.71	-	-	-	-	-	-	-	-	-	1.68	.95	-
Oil, gal/mg	-	-	-	-	-	-	-	-	-	-	-	-	119	23.1	11	27	18	-	-	-	-	-	-	-	-	-	-
Gas, Kcf/mg	-	-	5.47(3)	-	-	-	-	-	-	-	-	-	-	.005	-	-	-	1.41(7)	-	-	-	-	-	-	2.3	.4	-
Backwash KWH/mg Raw Water	-	3.8	-	9.1	-	-	2.6	2.4	-	0(6)	-	15	-	39	7.0	-	4.6	4.7	45	19	4.6	14	54	16	-	3.8	19
WATER																											
Backwash, %	-	3.4	1.9	1.1	1.5	-	1.9	1.2	-	-	2.8	2.3	1.3	3.8	1.2	-	2.0	2.1	5.2	4.4	1.3	2.3	9.2	2.7	3.4	1.9	2.2
Sludge Drain, Clarifiers, %											-	-	-	-	-	-			-				-		-		
Sedimentation Basin, %	0	.30	.76	.16	.41	.70	-	-	.38	.60	.94	.18			.06		.09	.14		1.31	1.01	.75		.86		.29	.17
CHEMICALS, lb/mg																											
Coagulant																											
Alum	157	69	239	116	184	514	429	100	80	586	339	220	.8	115	31	153	77	75	235	357	406	761	345	75	361	200	146
Iron Sulfate		270																									
Coagulant Auxiliary																											
Clay																											
$CaCO_3$																											
Na_2SiO_3														119													
$NaAl_2SO_4$																			86						13		64
Wisprofloc																									2.3		
Alkali																											
Hydrated Lime Equiv.		267	287	109	204	267	99	19	71	471	15	60						31(8)	14	107	335	426	150		241	244	
Type (4)	None	h	q	h	s	h	h	h	h	s	c	h	None	None	None	None	None	q	h	h	s	h	h	None	h	h	h
Disinfection																											
Chlorine	39(1,2)	43	34	22	10	30	36	22	29	31	14	9.4	13	30	19	8	12	36	40	44	15	40	55	22	37	69	22
Taste and Odor																											
Carbon	18(1)			2.5								4.4	.4				1.4			19						3.1	
$KMnO_4$	2.2(1)								1.3		1.1																
$NaClO_2$															.07												

NOTES:

(1) Plant is operated in parallel with a softening plant. Unit consumption given is for total operation.
(2) Chlorine consumption for both plants adjusted by amount required to oxidize ferrous sulphate used in softening plant.
(3) Plant uses gas engine regularly and electric energy for peaking.
(4) Symbols stand for hydrated lime, quick lime, soda ash, and caustic soda.
(5) Based on one month only.
(6) Automatic backwash and gravity raw water supply.
(7) This gas used for recarbonation, not heating.
(8) Plant sometimes is operated as a softening plant. Unit consumption applies only to the months in which softening was not carried on.

TABLE 13 Unit Costs (AVERAGE FOR PERIOD)

¢/Kgal of $\bar{U}$, Except as Stated

Chemicals, Excluding Flouride	.88	1.27	1.04	.65	1.30	2.30	2.00	.80	.53	4.40	1.78	.75	.23	.61	.24	.81	.33	.44	1.22	2.20	3.50	-	2.70	.60	1.77	1.23	.69
Energy, Total	1.59	1.89	.74	2.04	3.26	3.50	3.25	4.30	3.90	4.9	1.45	1.81	6.41	2.01	1.08	3.8	.93	2.68	2.02	-	-	-	4.30	1.46	2.96	1.63	1.15
Pumping	1.59	1.89	.74	2.04	3.26	3.50	3.25	4.30	3.90	4.8	1.42	1.72	4.63	1.79	.97	3.2	.75	2.68	2.02	-	-	-	4.30	1.46	2.89	1.61	1.15
Heating	-	-	-	-	-	-	-	-	-	.15(1)	.03(1)	.09(1)	1.78	.22	.11	.50	.18	-	-	-	.01	-	-	-	.07	.02	-
Heating, ¢/Kgal of Q_g	-	-	-	-	-	-	-	-	-	.04(1)	.03(1)	.04(1)	.82	.09	.06	.32	.13	-	-	-	.006	-	-	-	.02	.01	-
Manpower	1.41	2.0	1.44	2.74	8.5	6.1	11.00	7.60	1.5	7.6	.95	4.62	12.6	4.30	3.69	5.90	3.90	1.18	2.85	33.0	6.7	16.7	5.71	2.25	5.65	2.71	1.72
Manpower, ¢/Kgal of Q_g	.44	1.58	1.05	2.16	8.5	6.0	7.80	7.40	.91	1.98	.89	2.39	5.80	1.76	2.84	3.30	2.16	1.39	.88	7.26	6.7	7.38	4.82	3.08	4.80	1.79	.89
Maintenance and Repair	.10	.17	.47	.08	.88	.88	.61	1.3	.57	1.14	.65	.50	4.31	.05	.04	2.1	.70	.44	.36	-	.22	.67	.28	0	0	.20	.28
Miscellaneous	.10	.33	.10	.25	.33(1)	.33(1)	2.42	.18	.12	.42(1)	.12(1)	.23(1)	.24(1)	.27(1)	.03	.16	.19	.10	.35(1)	-	.03	-	.14	.18	.37(1)	.16	.21(1)
Miscellaneous, ¢/Kgal of Q_g	.03	.26	.07	.20	.11(1)	.11	1.65	.06	.03	.11(1)	.11(1)	.11(1)	.11(1)	.11(1)	.02	.09	.13	.12	.11(1)	-	.02	-	.05	.16	.11(1)	.11	.11(1)
Total Operating	4.06	5.96	3.79	5.76	14.27	13.11	19.28	14.18	6.62	16.46	4.95	7.91	23.79	7.24	5.06	12.77	6.05	4.84	6.80	-	-	-	13.13	4.49	10.75	5.93	4.01
Capital Costs (7.787% Actual 1964 Investment	10.4	-	4.70	9.36	-	20.7	15.1	8.31	-	53.6	1.38	4.72	25.5	9.40	-	11.40	4.21	4.02	8.60	-	7.15	24.5	17.4	8.87	17.8	6.67	5.17
Capital Costs, ¢/kgal of Q_g	3.23	-	3.42	7.34	-	6.87	10.4	2.65	-	13.9	1.27	2.94	11.7	3.86	-	6.42	2.98	4.75	2.66	-	4.65	6.18	6.05	8.77	5.29	4.41	2.66
Total Cost at Actual $\bar{U}$	14.48	-	8.49	15.12	-	33.81	34.38	22.49	-	72.06	6.25	12.63	49.29	16.64	-	24.17	10.26	8.85	15.40	-	-	-	30.53	13.36	28.55	12.60	9.19
Total Cost at $\bar{U}$ = 1.0	6.23	-	6.72	12.46	-	19.28	25.60	15.94	-	25.81	6.12	8.10	26.22	8.24	-	15.71	7.07	9.86	7.09	-	-	-	18.09	14.07	14.88	9.32	5.67

NOTES:

(1) Missing data supplied as described in text.

CHAPTER 5

DISTRIBUTIONS OF OPERATING RATIOS AMONG PLANTS

5-A EXPLANATION

This Chapter summarizes the comparative data on the design factors, operating ratios and other factors for the plants interviewed. The purpose is to allow individual plants to assess their performance relative to other plants in terms of the percentile level which they hold among all plants. The values for each factor were arranged in order of increasing magnitude and plotted on arithmetic- or log-probability paper at plotting positions determined by the formula:

$$\frac{100\ n_i}{n+1}$$

where:

n_i = rank number of individual plant
n = total number of plants for which data were available

If the data plotted in this manner fitted a straight line on arithmetic-probability paper the distribution was called normal. If the points on log-probability paper gave a better approximation to a straight line the distribution was called log-normal. The tables beyond show the readings from this straight line at the 10 percentile, the 50 percentile or median level, and at the 90 percentile level. For the benefit of the statistican reader there is also included a technical term, the σ ratio, which measures the variance of the data points. The higher the σ ratio the greater the variability among the data. For the benefit of the plant manager not familiar with statistical terminology and who still wishes to approximate his percentile level the following explanation is offered.

The 50 percentile level is that value of the factor above which lie 50 percent of the plants and below which lie the other 50 percent. The 10 percentile value is that above which lie 90 percent of the plants and below which lie 10 percent. Thus if an individual plant has a factor which coincides with the 10 percentile level in the table it means that 90% of the plants have values of the particular factor which are greater than that for the individual plant considered.

If the plant manager should wish a more exact placement of his percentile level this may be done by plotting on arithmetic- or log-probability paper the values at the 10% position, the 50% position and the 90% position and drawing a straight line through them. He can then read in at the actual value of the factor for his plant and read down from the intersection with the straight line to the percentile level represented. Probability paper may be obtained at engineering supply stores. One arithmetic-probability paper is Keuffel and Esser Co. No. 359-23 and one log-probability paper is K&E 359-24.

Where the distributions are not represented by a single straight line such plotting may still be done by utilizing the intersection percentile which is described in the text commentary for these two-part distributions. If the intersection lies above 50% then the

lower straight line is obtained by drawing through the 10 and 50 percentile points. The intersection of this line with the intersection percentile provides a point on the second line which therefore passes through that point and the 90 percentile point. A corresponding procedure will provide the two straight lines when the intersection is below 50%.

Where it seemed likely or possible that there might be a difference between the factor values for large and small plants the distributions were run separately for the two types. Where there seemed little likelihood of such a differentiation or where the separate plots show no differentiation both large and small plants were included in one distribution.

The details of the σ ratio will be of interest to the statistician. The σ ratio is a term particularly applicable to log-normal distributions. It is the ratio of the value at one standard deviation from the median or at one standard error of estimate from the regression line to the value at the median, or roughly the ratio of the 84 percentile value to the 50 percentile value; or of course on the low side of the median it is the ratio of the median value to the 16% value. When the σ ratio is given for a distribution described in the tables as arithmetic it is the 84 percentile to 50 percentile ratio, (since for an arithmetic distribution the upper and lower ratios are not the same). When the σ ratio is given for a distribution described as two-part whether logarithmic or arithmetic that ratio has been obtained from the actual standard deviation of the absolute values computed in the conventional manner. When the distribution is indeed arithmetic the absolute standard deviation is the product of the median x (σ ratio -1). Where the distribution is indeed logarithmic the σ ratio computed in this way from absolute arithmetic values will be higher than a σ ratio computed as the standard deviation in log units from the logs of the points. Because the main purpose of the σ ratio in the tables is to show the general extent of the dispersion it was not thought worthwhile to undertake the extra computation required to compute the log standard deviation for the two-part log distributions. In a few cases the σ ratio given is that describing the slope of one or the other of the two lines. This was done especially where the second of the two lines made up only a small portion of the distribution or had a σ ratio of 1.0

5-B DESIGN FACTORS

Table 14 shows the distribution of design factors. Special points concerning particular factors are discussed in the following text.

TABLE 14

Distribution of Design Factors	No. of Points	Dist'n. Type	Value of Factor at 10%	50%	90%	σ ratio
Mix. basin, detention, min.	9	log	.242	1.54	9.95	4.31
Floc basin, detention, min	20	log	13	30	71	2.00
Sed. basin, " , min	20	log	174	270	426	1.40
SSCC basin, " , min	31	log	40	98	230	1.90
Sed. surface loading, gpm/sf	20	log	.20	.34	.56	1.50
SSCC loading , gpm/sf	6	log	.32	.95	2.8	2.30
Sed. transport rate, fpm	23	log	.10	.30	.94	2.20
Filter rate, gpm/sf	22	see text	1.57	1.87	1.99	1.08
Manpower, large, man hr/mg	14	arith	3.15	6.65	10.2	1.41
Manpower, small, man hr/mg	13	see text	13	40	48	1.35

Mixing Basin Detention — The data for mixing basin detention time covers only those plants actually having mixing basins and does not include those in which mixing is accomplished in the influent pipe.

Sedimentation Basin Detention Time — As was to be expected the sedimentation detention for clarifiers is considerably lower than that for conventional sedimentation basins. Some design specifications allow a 20% reduction in sedimentation detention if mechanical sludge removal is used since it is not necessary to provide space for the accumulated sludge. An analysis was attempted of the correlation between mechanical sludge removal and sedimentation detention time but only two plants had mechanical sludge removal. The design detention times of these two plants were higher than the median for the plants without mechanical sludge removal, rather than lower. Accordingly the data of the present study do not show any reasonable correlation between mechanical sludge removal and detention time and the two mechanical sludge removal plants were incorporated in with the other plants in developing the distribution figures.

SSCC Detention Time — The interview sample contained only six plants with suspended solids contact clarifiers. However, the AWWA Committee on Capacity and Loadings of Water Treatment Processes has presented a report (5) on a questionnaire survey of suspended solids contact units in which there are listed preferred detention times for 24 plants and percentages of sludge drainage (a production factor) for 18 plants. The capabilities of the Committee units were not specified but it is unlikely that size of unit is correlated with detention times and sludge drain percentages. Accordingly the six plants from the present study have been combined with the Committee plants and the distributions for these two parameters listed in the tables are those for the combined group.

Sedimentation Basin Transport Rate — The distribution curve for the upflow transport rate in the three suspended solids contact clarifiers was identical with that for transport rate in conventional sedimentation basins.

Filter Rate — The distribution of filter rate is best represented on arithmetic-probability paper but even then cannot be represented by a single straight line. Two straight lines are required intersecting at the 59 percentile. It will be noted that the dispersion in filter rate is very low compared to the dispersion in other factors.

Design Manpower — Design manpower for the small plants is best represented on log-probability paper but must be represented by two straight lines because of the number of plants at 48 man hours/mg, as described beyond. The two straight line portions intersect at about the 58 percentile. The σ ratio given is that for the lower percentile line, the σ ratio of the upper line of course being 1.0.

Figure 1 shows the design manpower for the interviewed plants. The diagonal auxiliary grid lines are lines of constant men per shift values.

When the plant is not capable of unattended operation at least one man per shift is required. This is typical of the small plants and results in the group of points at 0.5 mgd and 48 man hours/mg. The rest of the small plants are all capable of operation unattended during some portion of the day by virtue of having automatic controls on raw

DESIGN MANPOWER

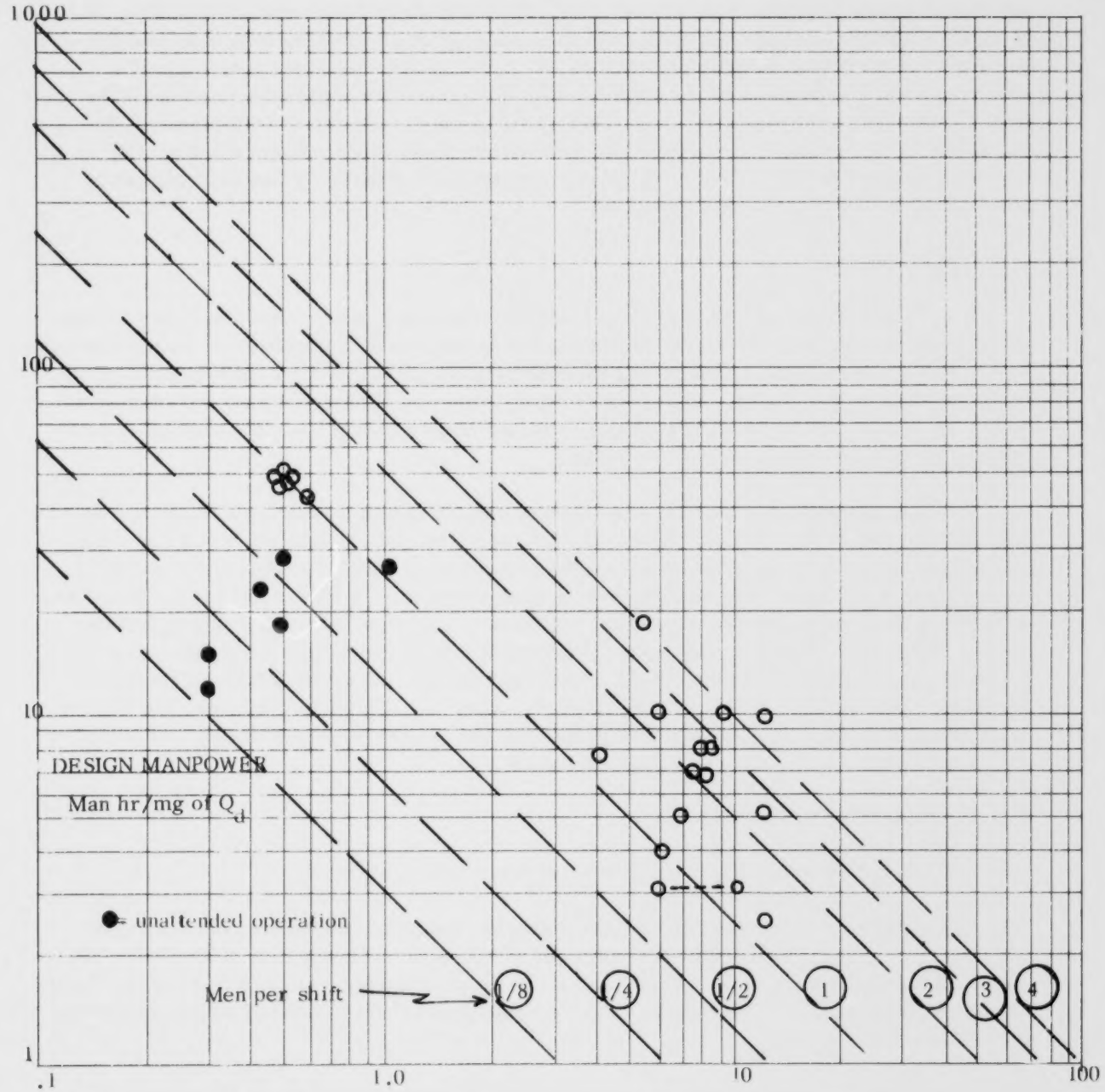

FIGURE 1
LK-R #426

water pumping or supply system, on feeders, and on finished water pumping. The extent of the possible reduction in manpower as a result of the unattended capability is clearly shown.

None of the larger plants utilized periods of unattended operation although one had the automatic controls necessary for such. All of these plants were operated 24 hours per day and were attended 24 hours per day, the variation in manpower arising from the use of various numbers of men per shift. (In the one large plant showing less than one man per shift the plant was actually attended on all shifts but the operators took care of a softening plant run in conjunction with the filter plant but with separate equipment. The total design manpower was allocated on the basis of the production of both plants). Remarkable is the variance in design manpower among these larger plants all operating on the same general basis. Five of the plants operate with about 1.5 man per shift while others utilize 2 to more than 4 men/shift.

5-C UNIT PRICES

Table 15 shows the distribution data for the unit prices. For purchases prices are greater for the smaller plants indicating the savings in bulk purchases. Labor prices are typically lower in the small plants representing no doubt the labor market conditions in the smaller communities. For general labor there was a differentiation between small and large plants but the small prices were greater than the large and this seemed anomalous so the two distributions were combined.

An analysis was made to test whether the automatic plants capable of unattended operation tended to have higher unit prices for labor than the nonautomatic plants. Automatic plants of course would be particularly advantageous under circumstances in which labor prices were high. The sample data indicates that this is indeed the case. There were only four plants in the sample capable of unattended operation, two small plants and two large. All of these plants stood in the 70-86 percentile levels in unit labor prices for operators and maintenance personnel. This suggests that indeed high labor prices are associated with automatic plants. Which is the cause and which the effect was not determinable from the data. The actual labor prices for the automatic plants were of the order of 30% higher than the median prices for all plants.

5-D PRODUCTION FACTORS

Table 16 shows the distributions of production factors.

Utilization Factor — As was true for the universe described in Chapter 3-A the utilization factor for large plants tends to be larger than for small. The median for small plants in the sample was 0.39, corresponding well with 0.38 in the class population (Chapter 3). The median for large plants was 0.60 compared with 0.47 for the class population.

Sedimentation Detention — This is a two part log distribution intersecting at 57 percentile. The σ ratio given conforms to the practice enunciated in Section A.

TABLE 15

Distribution of Unit Prices	No. of Points	Dist'n. Type	Value of Factor at 10%	50%	90%	σ ratio
Superv. labor, large, $/hr	14	log	1.73	3.35	6.51	1.67
Superv. labor small, $/hr	6	"	1.35	2.12	3.35	1.42
Op & Maint labor, large, $/hr	14	"	1.65	2.40	3.50	1.34
" " " , small, $/hr	13	"	1.31	1.75	2.30	1.23
General labor , $/hr	9	"	1.04	1.58	2.40	1.39
Elec. energy, large, ¢/KWH	14	"	.65	.92	1.30	1.32
" " , small, "	11	"	.98	1.48	2.22	1.36
Oil, ¢/gas/gal	5	"	9.8	12	18.2	1.40
Alum, large , ¢/lb	13	"	2.37	2.65	3.00	1.09
Alum, small, "	11	"	3.31	3.89	4.50	1.13
Alkali, large, ¢/lb, h.l. equiv.	11	arith	.68	1.14	1.60	1.32
Alkali, small, ¢/lb " "	10	"	.35	2.40	4.10	1.53
Chlorine, large, ¢/lb	14	log	4.15	5.20	9.10	1.62
Chlorine, small, "	12	"	9.10	12.50	17.50	1.30
Carbon, "	10	arith	8.50	11.80	15.20	1.29

TABLE 16

Distribution of Production Factors						
Utilization factor, large, fraction	13	log	.31	.60	1.14	1.66
" " small, "	14	"	.21	.39	.74	1.64
Sed. detention, min	21	see text	200	348	1700	1.91
SSCC " "	30	log	43	120	320	2.12
Filter rate, gpm/sf	25	see text	1.0	1.61	2.85	1.34
Rational filter run, Kgal/sf BW	25	arith	1.50	4.75	8.00	1.54
Average raw water quality						
Turbidity, ppm	24	log	3.5	19	115	3.84
Temp. ^{o}F	23	arith	47	60	72	1.16
Alkalinity, total, ppm	25	"	6	88	170	1.73
" , phenolp., ppm	10	see text	0	0	8.2	---
Free CO_2, ppm	10	see text	0	4.8	11.7	2.10
pH	25	arith	6.88	7.50	8.13	1.06
Hardness, total, ppm	24	arith	32	103	173	1.53
" non-carb., ppm	10	see text	0	9.5	53	3.79
TDS, ppm	13	arith	40	140	240	1.57
Color	16	see text	4.5	11.5	150	8.50

Clarifier Detention — It is noted that the detention time in clarifiers includes that in the mixing and flocculation portions of clarifiers and therefore is comparable with the sum of the detention times for conventional sedimentation basins and their associated flocculation basins and mixing chambers.

Filter Rate — Filter rate distribution is three-part log with the major segment between 15 and 85% having a lower slope than the extremes. The production filter rate has a greater variance than the design filter rate of course because of the variations in $\bar{U}$.

Average Raw Water Quality — Distributions of average raw water quality are less meaningful than distribution of other production factors, design factors, etc. because the latter in some measure may be used as estimators of the distribution of the universe of the treatment plants, but the former simply represent the distribution within the sample actually taken. In other words there is good reason for believing that the sample of plants is representative as to operating and design practices but it was not particularly selected to be representative of raw water qualities. For one thing in order to have the distributions of raw water quality in the sample correspond to the universe it would have been necessary to geographically proportion the sample according to the treatment plant populations of the several geographical regions. Nevertheless the distribution data are presented as showing the characteristics of the sample source waters.

Phenolphthalein Alkalinity — This distribution is two-part arithmetic because about 60% of the sample had 0 phenolphthalein alkalinity and 60% therefore is the intersection of the two straight lines.

Free CO_2 — Distribution of free CO_2 is also two-part arithmetic for the same reason as for phenolphthalein alkalinity the intersection point being about 20%.

Non-Carbonate Hardness — 28% of the sample had zero non-carbonate hardness. The distribution was log-normal above 28%.

Color — Color showed a two-part log distribution with intersection point at about 65%. The σ ratio of 8.50 has been computed in the prescribed manner. As for all such computations the σ ratio is somewhat higher than would correspond to the standard deviation of a log-normally distributed set of data. However in this case the computed σ ratio is considerably greater than the corresponding log deviation because the color values have such a wide range in absolute magnitude.

5-E UNIT CONSUMPTIONS

The distribution of unit consumption factors is shown in Table 17.

Manpower — In the chemical process industries some attempts have been made to correlate operating labor as a function of plant capability. A good correlation is obtained among various types of plants if the complexity of the operation is taken into account in terms of the number of unit operations or process steps involved in each plant (6). For example, the manufacture of ethanol from molasses requires five

TABLE 17

Distribution of Unit Consumptions	No. of Points	Dist'n Type	Value of Factor at 10%	50%	90%	σ ratio
Manpower, large, man hr/mg	14	arith	5.1	10.5	15.9	1.39
Manpower, small, man hr/mg	13	arith	12	53	91	1.57
Basin cleaning, man hr/mg	19	log	.0052	.073	1.07	7.67
Pumping energy large, KWH/mg	14	log	980	1800	3270	1.59
Pumping energy, small, KWH/mg	10	log	1440	2250	3500	1.42
RW energy large, KWH/mg	4	log	310	740	1750	1.96
RW energy, small, KWH/mg	3	log	820	1100	1500	1.27
FW energy, large, KWH/mg	4	log	640	900	1290	1.32
FW energy, small, KWH/mg	3	log	970	1350	1950	1.33
Oil, gal/mg	5	log	9.5	21	48	1.90
BW energy, KWH/mg	18	log	2.1	10	48	3.40
Backwash, %	22	log	1.03	2.21	4.70	1.81
SSCC sludge drain, %	19	log	.60	2.4	9.8	3.00
SED cleaning, %	19	see text	.060	.390	1.07	1.95
Chemicals, lbs/mg						
Alum, large	14	log	50	121	300	2.00
Alum, small	13	see text	58	320	710	1.67
Alkali, hyd lime equiv., large	9	log	11	80	57	4.56
Alkali, hyd lime equiv., small	10	log	78	200	52	2.10
Chlorine	27	log	11.8	25	53	1.80
Carbon	7	log	.62	3.20	16.2	3.75

steps – yeast preparation, fermentation, beer distillation, aldehyde distillation, and final rectification. The correlation of man hours per ton per step with plant capability tons/day is log-log linear and has a reasonably high correlation coefficient. Computations were made to determine just how water treatment plants compared with such a correlation. This had to be done by extrapolation of the chemical process correlation curve since the largest chemical plant is only about as large as the smallest water treatment plants in the study. The small plants in the study have a design capability of the order of 2000 tons/day of product (water) and the large plants of the order of 30,000 tons/day. Considered as separate unit operations requiring operator attention a water treatment plant has of the order of 4-6 process steps divided about as follows:

Pumping (raw water and finished water together)
Mixing and chemical feeding
Flocculation
Sedimentation
Filtration

When the chemical process correlation line and the data from the present study are plotted on the same sheet it is obvious that the man hours/ton step for water treatment is much less than the corresponding manpower for chemical processing. The labor requirements for water treatment per step are of the order of 1/20th and 1/30th the labor requirement for chemical process plants of similar size and complexity.

It should be pointed out that a wet processing chemical plant will actually handle an amount of material considerably greater than the amount of product produced because the amount of product is contained in a liquid carrier. For example, a soda ash plant will actually process an amount of material about 5 times as great as the amount of product produced. However, even taking this factor into account the water treatment plant still would have a unit labor requirement of the order of 1/4th-1/6th that of a comparable chemical plant. For comparison of the actual magnitudes the man hours/ton step for the largest chemical plants is of the order of 0.05 while for the smallest water plants in the study it is about 0.001 and for the larger water plants in the study of the order of 0.0003.

Pumping Energy — It is noted that the pumping energy for small plants is in all categories greater than that for large plants and the difference is of a magnitude as to be unmistakable. In the median the differences are of the order of 25% for total pumping energy and 40-50% for raw water and finished water energy separately.

The study does not provide really adequate data for a study of the causes of this difference but such data as is available do suggest that the smaller plants tend to have higher TDH and lower pumping efficiency than the larger plants. Physically one can well imagine that the larger cities tend to be located closer to the elevation of their water sources than do the smaller cities. At least very few larger towns are located at high altitudes in regions of high relief. Also, although it is not certain that the pipelines in the sample are optimized, if they are optimized the optimum friction head for higher capabilities is substantially lower than that for lower capabilities.

In the course of making the preceding analyses, pumping efficiencies were computed for plants for which the data were available. These are shown in Table 18. This table suggests that conventional efficiencies of 65-75% frequently used in generalized economic computations (by the present authors and others) might well be revised downward for practical application in water treatment plants, to about 55% to represent average conditions.

TABLE 18

PUMPING EFFICIENCIES, %

Plant No.	RW Pumping	FW Pumping	Total Pumping
4	71		
5	65	51	56
7	51	39	43
17		55	
18			48

SSCC Sludge Drain — The study contributed only one figure for wastage of water in draining sludge from clarifiers but data were utilized from the AWWA Committee Survey (5) described in Chapter 5-B under SSCC Detention Time.

Sedimentation Basin Cleaning — The percentage of water utilized in cleaning the sedimentation basins follows a two-part log distribution with an intersection at about 64%.

Alum Consumption — The alum consumption for small plants has a two-part log distribution with intersection at about 66%.

5-F UNIT COSTS

Table 19 shows the distribution of unit costs in ¢/Kgal. Included are some unit costs under design conditions. Unit costs in general are a product of unit prices and unit consumptions. In cases where there is a difference, unit prices are larger in the smaller plants -- except for manpower. Also unit consumptions tend to be higher in the smaller plants so that for all cost components the units costs are higher in the smaller plants.

Design Manpower — The design manpower cost for small plants is a two-part log with intersection at about 66%.

Maintenance and Repair — The distribution of MR unit cost for large plants is two part log with intersection at 61%. For small plants it is a single log line to 21% at which point the value falls to zero. This zero of course is not a real factor but only indicates that the persons interviewed were unable to recall any MR expenditures (other than carried on by operators). In some cases where the plant was practically brand new the zero was the actual experience to date.

Heating Cost Data — Distributions of heating costs are not shown because they have a rational correlation with climate. Consumptions and costs for heating were obtained for only eight interviews. In the South, heating costs were so small that they could not be separately determined and in general are included in the miscellaneous costs. Heating costs are no doubt correlateable with Q_d measuring the square feet of heated space and with the standard heating degree-days. It was not warranted to correlate with heating degree days in the present study, but instead heating may be compared on the basis of the climatic measure already

used, namely average number of days below 32°F. Where days below 32° were 60-80 heating costs were of the order of 0.01-0.02 ¢/Kgal of Q_d. Heating costs below 80 days may thus be considered as 0.0 ¢/Kgal. Five of the plants in the 140 day climatic zone showed heating costs of about 0.1¢/Kgal of Q_d for the large plants and 0.3 and 0.8¢/Kgal for the small plants.

In filling missing data on heating costs in each size category a linear interpolation on days below 32°F starting at 80 days was used, between 0.01 and 0.5¢/Kgal for the small plants and between 0.01 and 0.1¢/Kgal for the large.

TABLE 19

Unit Costs, ¢/Kgal	No. of Points	Dist'n Type	Value of Factor at 10%	50%	90%	σ ratio
Chemicals (ex F), large	14	log	.29	.70	1.68	1.97
" " , small	12	"	.49	1.45	4.30	2.34
Energy, pumping, large	14	"	.80	1.57	3.10	1.97
" " , small	10	"	2.40	3.45	5.05	1.34
Manpower, large, (per $\bar{Q}$)	14	"	1.05	2.20	4.55	1.77
" small "	13	"	2.90	7.80	21.0	2.18
Design manpower, large, (per Q_d)	14	"	.60	1.30	2.90	1.86
" " small "	13	see text	2.60	6.10	8.15	1.32
MR, large	12	"	.03	.280	.70	1.32
MR, small	8	"	0	.52	4.75	5.58
Misc (per $\bar{Q}$)	15	log	.064	.150	.355	1.94
Misc (per Q_d)	15	"	.025	.082	.310	2.80
Total operating, large	14	"	3.95	5.50	7.64	1.29
Total operating, small	10	"	8.80	14.0	22.2	1.43
Capital recovery, large	10	"	3.37	5.85	10.3	1.56
" " small	10	"	7.20	17.0	40.2	1.97
" " large (on Q_d)	10	"	2.00	3.42	5.90	1.53
" " small "	10	"	4.00	7.20	12.4	1.53
Total costs at actual $\bar{U}$, large	10	"	6.6	11.2	19.0	1.51
" " " small	8	"	13.5	32.0	76.0	1.97
Total costs at $\bar{U}$=1.0 large	10	"	5.4	7.8	11.3	1.35
" " " small	8	"	13.6	19.6	28.0	1.33

CHAPTER 6

INVESTMENT COSTS

6-A INVESTMENT COST CORRELATION

Table 10 lists for each plant where available three different unit investment costs. One of these is the investment adjusted to 1964 for the actual existing plant. This investment was used in developing the unit fixed costs on the investment, ¢/Kgal, shown in Table 13 for each plant. The second unit investment is the preceding deregionalized so as to remove the dispersion caused by local price levels and to show what the actual existing plant would cost at national average prices for comparison with other plants. The third unit investment not only adjusts to 1964 and deregionalizes but also adds a cost of a raw water pump station to those installations not having such. This cost shows the national average 1964 investment in a standard plant, comprising intake structure if of simple form, raw water pump station, treatment plant itself and associated finished water pump station. It is the last of these unit investments which is used in the analyses in this chapter, and is to be used in the correlation of investment with raw water quality parameters.

Figure 2 is a plot of unit investment where available against raw water design capability. Twenty-one data points (excluding the one slow sand filter plant) were used to develop a regression line which has the following characteristics:

Type of distribution about median	log normal
Regression equation	¢/gpd = 30.7 $Q_d^{-0.323}$
Standard error of estimate, log units	0.164
σ ratio	1.46
Correlation coefficient	0.768
Fraction of variance removed	0.590
Significant at 0.001 level	Yes

The individual points are distributed log-normally about the regression line. The slope of the log-log regression line is -0.323. This means that the total investment varies with the 0.68 power of the capability, a value which is in the typical range for chemical processing plants.

The standard error of estimate in log-units is 0.164 which signifies that 68% of the data points may be expected to lie in a range between 68% and 146% of the regression line. (The standard deviation for each size group separately is about 0.182 log units). The correlation coefficient is 0.768 and the fraction of the total dispersion removed by the Q_d correlation is 0.59. It should be recognized that the fraction of the variance removed may be expected to be low because the range in Q_d is low and therefore the range in costs is comparatively small. The range in Q_d is only from about 0.5 to 7.0 mgd, a span of about 14 fold. If the interviewed plants had covered a much wider range of Q_d, say from 0.05 to 500 mgd it is likely that the width of the dispersion band would have been about the same and thus the fraction of the variance removed would be considerably higher. This remains to be explored when a full scale study of investment costs over wide Q_d ranges is undertaken.

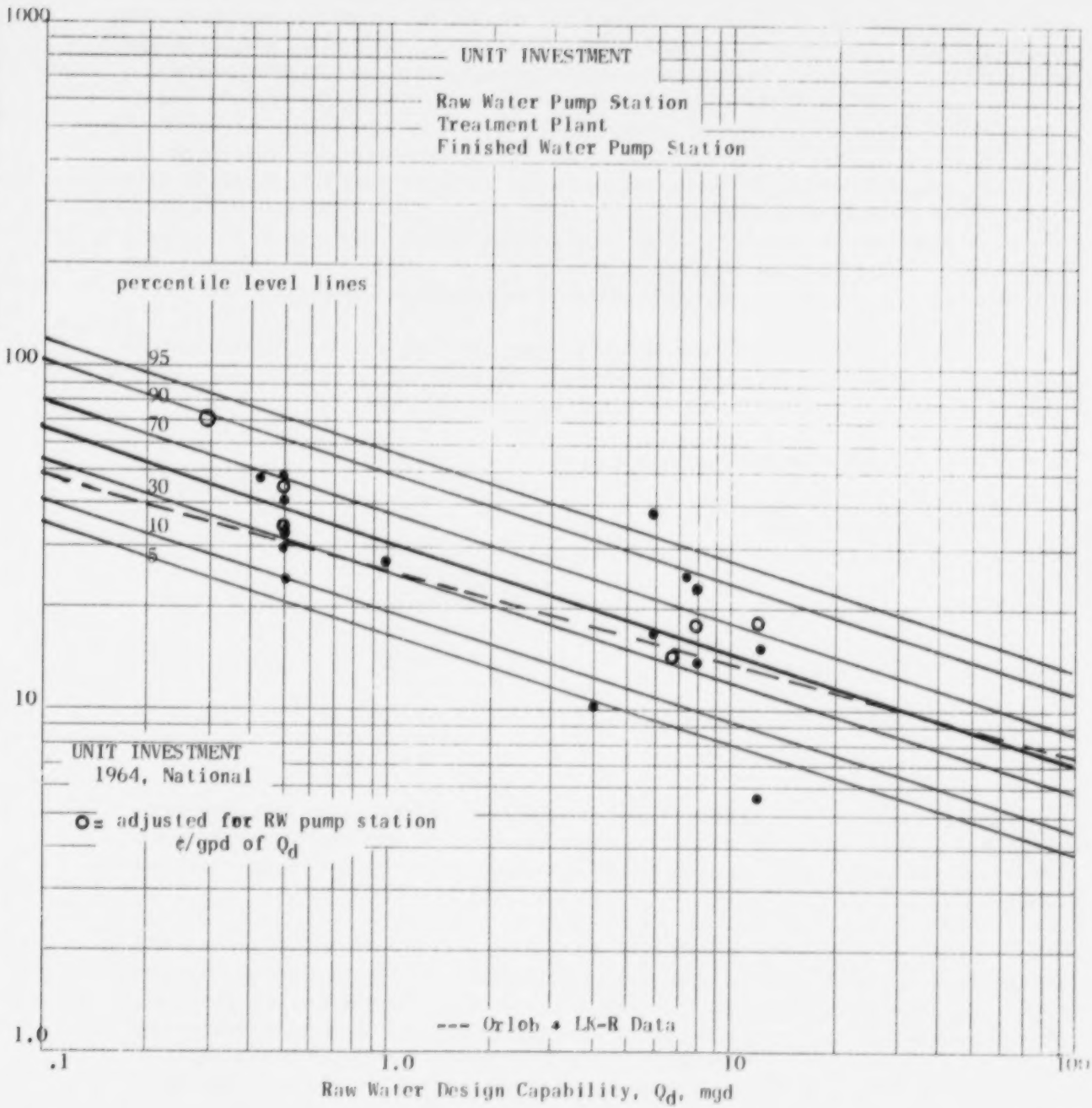

FIGURE 2

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A similar regression analysis was performed for 20 of the 22 plants of the present study, plus the 23 plants from the Orlob-Lindorf study (3) for which data were available. The combined regression line is shown as the dashed line on Figure 2. The combined line is lower than the Figure 2 line at low Q_d largely attributable it is thought to several small plants in the Orlob-Lindorf study which had exceptionally low investment costs. The correlation coefficient was only 0.57. Because of this lower degree of correlation it was decided not to use the Orlob-Lindorf data in subsequent analyses.

6-B EFFECT OF TYPE OF CONSTRUCTION AND EQUIPMENT

An exploration was undertaken to determine whether the remaining dispersion could be attributed to one or more of several physical differences among the plants. To do this a modal plant type was established and attention was directed to those plants for which cost data were avilable and which departed in some degree from the modal type. The modal type had filters which were housed, had conventional sedimentation basins rather than suspended solids contact clarifiers, had basins or clarifiers in the open, i.e. not housed or covered, and were not capable of automatic (non-attended) operation. The following Table 20 shows the interviewed plants having available investment costs which departed from the modal type, and gives measures of their departure from the median investment at their design capabilities, namely the deviation ratio, i.e. the ratio of the actual investment cost to the median. It is emphasized that the conclusions to be drawn from such a small sample must be considered highly tentative and subject to possible change when a larger sample is taken.

Looking at the data over-all, one is struck with the fact that not a single one of these non-modal type plants shows a deviation in investment cost as great as one standard deviation of the total data. This means that all of these non-modal plants lie in the same band with 68% of all plants. In other words the over-all dispersion of the investment data is much greater than the dispersion of the particular non-modal plants in the sample. However, as will be mentioned beyond, the size and composition of the sample does not permit this statement to be extended to the universe of non-modal plants.

Some quantitative exploration of the effect of non-modal plant type on investment cost can be made from data collected incidentally in the study. Of course the proper way to study for example the effect of housing the sedimentation basins would be to make detailed cost estimates on specific plants with and without housed basins. A semi-quantitative study of this type was performed on the housing of sedimentation basins and filters. Assuming that basins and filters could be housed at a cost of $15/sq ft of housing and covered at a cost of $2.00/sq ft of covering, the plants non-modal in Table 20 in these respects were adjusted to the modal type, that is, by subtracting the housing or covering of sedimentation basins or clarifiers and adding the housing of filters, (including a two-foot walkway for access).

The results shown in columns 8 and 9 of the table indicate that the cost of non-modality in housing of filters and sedimentation basins is only of the order of 0-4% of the median plant cost for the corresponding capability. Thus it does not change very much the ratio of the adjusted plant investment to median investment. The new ratios, expressed in Column 9 are those for plants from which all non-modality except that of having suspended solids contact clarifiers or having unattended capability has been removed.

NON MODAL PLANTS HAVING INVESTMENT DATA

TABLE 20

1	2	3	4	5	6	7	8	9	10
	Type of non-modality								
No.	Filters open	Sed. covered	SSCC housed	Have SSCC	Have unattended operation	Deviation Ratio Investment / Median Inv.	Change for housing or covering	Adjusted* Deviation Ratio	Has remaining non-modality
3	1/2 (1)					1.12	.02	1.14	
22				X		.86	.00	.86	X
28	X			X	X	.82	.03	.85	X
29	X					1.42	.04	1.46	
14			X	X	X	1.06	-.04	1.02	X
1	X					.95	.03	.98	
15			X	X	X	1.29	-.04	1.25	X
17		X				1.09	.00	1.09	
19	1/2 (2)					.86	+.02	.88	
10					X	1.39	.00	1.39	X
27					X	.97	.00	.97	X

* All non-modality removed except SSCC and unattended operation

(1) Half housed, half open

(2) Half housed, half covered

Unfortunately the data are not extensive enough for a statistical analysis of the separate effects of these two types of non-modality, since three of the six plants have both types. As a whole these data are not inconsistent with a hypothesis that clarifiers reduce investment costs while unattended operation capability increases it. However, more data would be required to statistically test this hypothesis.

A semi-quantitative exploration of clarifier costs is based on a few values for installed costs of sedimentation basins and suspended solids contact clarifiers as individual pieces of equipment, developed incidentally in the study. In Figure 3 these few investment costs are plotted on the upper ordinate against the volume capacity of the unit. It may be seen that clarifiers do not show any strong tendency to cost more than sedimentation basins of the same volume. Indeed only one of the three clarifiers shows a cost higher than the trend line of the sedimentation basins. However, clarifiers have a considerably greater Q_d capability than sedimentation basins of the same volume because the customary detention times are shorter, typically about one and one-half hours for clarifiers as compared with four hours for conventional sedimentation basins. In the right hand portion of the Figure the same data have been plotted against raw water capability Q_d on the lower ordinate on the basis of these typical detention times. It is seen that two of the three upflow clarifiers show costs considerably below sedimentation basin costs. One of these is about one-half the correspnding sedimentation basin cost and the other about one-fourth. The third clarifier is about 25% higher than the sedimentation basin cost.

In the four plants for which estimates were available (Table 23) the sedimentation basin averaged about 14% of the total plant investment. Accordingly substitution of a clarifier ought to lower the total investment by something of the order of 1/2 to 3/4 of 14% or about 8-10% of the total investment. The true and proper answer can only be obtained by a cost engineering analysis of the relative costs of clarifiers and basins which is not attempted here. Suffice it to say that so far as the data from the present study are concerned the change in investment ascribable to clarifiers as against sedimentation basins is minor compared to the general dispersion of the investment data.

6-C INFLUENCE OF CLIMATE ON TYPE OF CONSTRUCTION AND EQUIPMENT

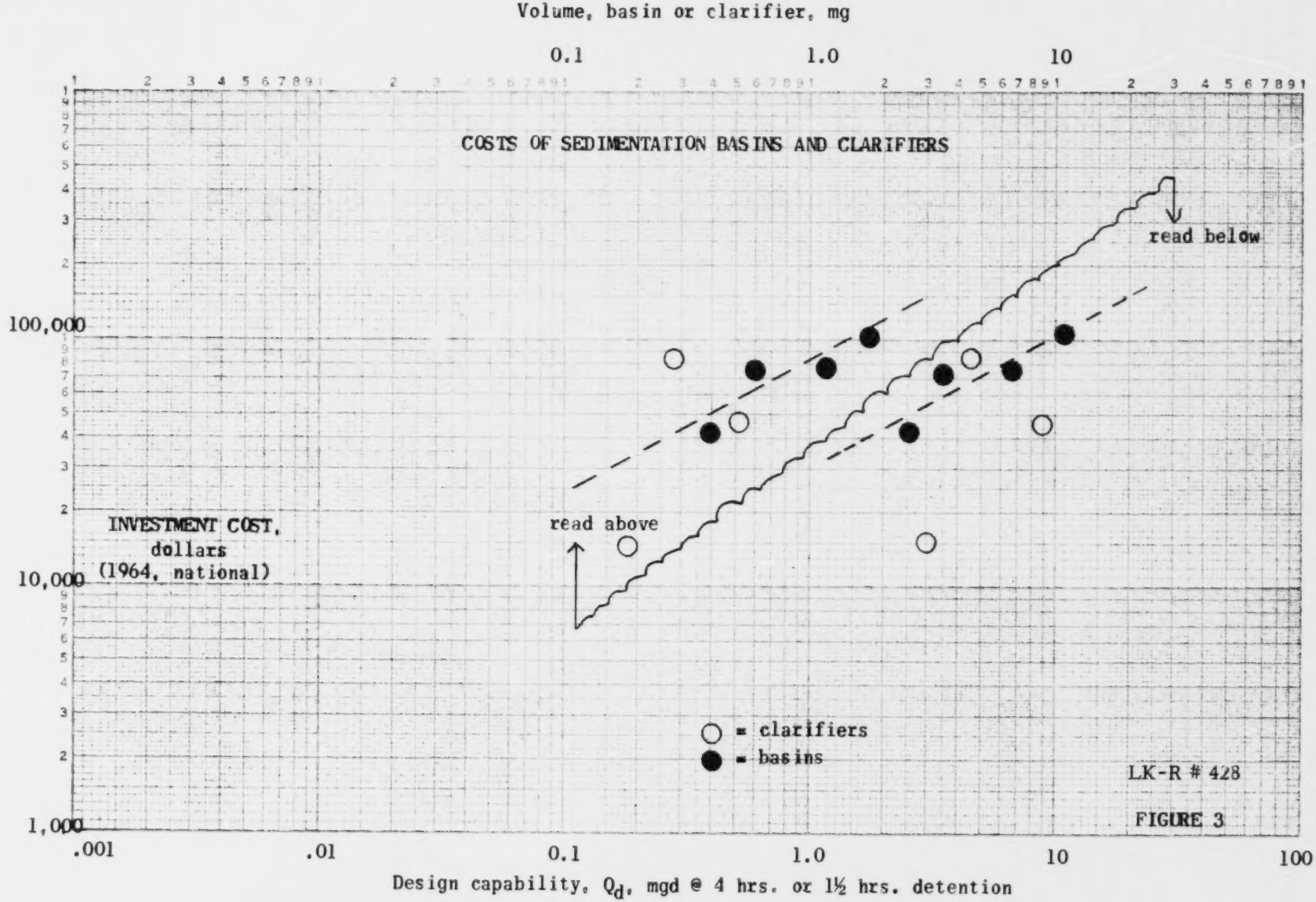
Table 21 shows the incidence of non-modality in housing filters and basins and in having clarifiers as influenced by climate, measured by the average number of days per year with minimum temperatures below 32°F.

TABLE 21

INCIDENCE OF NON-MODALITY AS INFLUENCED BY CLIMATE

Percent of plants having non-modal characteristics

Non-modal Characteristic	Days/year below 32°F				
	0-30	30-70	70-100	100-140	140-150
Filters open	100	30	0	n.d.	0
Basins housed	0	0	0	n.d.	80
SSCC	0	27	0	n.d.	60


Volume, basin or clarifier, mg
0.1
1.0
10
COSTS OF SEDIMENTATION BASINS AND CLARIFIERS
read below
read above
100,000
10,000
1,000
INVESTMENT COST,
dollars
(1964, national)
○ = clarifiers
● = basins
LK-R # 428
FIGURE 3
.001
.01
0.1
1.0
10
100
Design capability, Q_d, mgd @ 4 hrs. or 1½ hrs. detention

The table was prepared by plotting the type with respect to these three characteristics against the days/year. With respect to filters the modal type is that they be housed but the milder the climate the greater the percentage of plants which have open filters. In the South with 0-30 days per year all interviewed plants had open filters. With respect to housing of bains the modal type is that the sedimentation basins or clarifiers be unhoused. However in the severe climates having 140-150 days per year below 32°F most plants have housed basins or clarifiers. It has already been shown that the effect on investment cost of housing the clarifiers is rather small. But rough figures from the incidental study data show that a 1 mg capacity sedimentation basin will cost about $8.00 per sq ft of surface area, but the housing of this square foot will cost just twice that figure. If housing the clarifiers adds about 4% to the investment cost then housing sedimentation basins having three times the area of the clarifiers would add 12% to the cost. Thus the housing of sedimentation basins, as distinct from the housing of clarifiers, would represent an appreciable fraction of the total investment. It is likely therefore that in the severe climates clarifiers have an economic advantage not so much because of their inherent cost compared with sedimentation basins but because of the much lower cost of housing them. If that is the case one would expect to find a high incidence of suspended solids contact clarifiers in the severe climates. The third row in Table 21 shows that the interview samples confirm this to some extent. Of the five plants interviewed in the 140-150 day class three had housed clarifiers, one had covered sedimentation basin, and one had open sedimentation basin. There were some clarifiers in the 30-70 day region but climate was not the deciding factor since these were not housed.

6-D CONTRIBUTION OF INVESTMENT COMPONENTS

It is possible to extract from the data some general concepts concerning the relative contributions of various components to the total investment. The data actually are not well suited to such a study because it is not customary in engineering estimates, in bid documents or in appraisals to break down the investment into those components of interest to the design and operating engineer. A common breakdown for example is between buildings and equipment. But with such things as filter walls, sedimentation basin walls, and clear wells, comprising part of the building foundation it is obvious that some of the conventional building costs are really equipment costs. Even where there is a breakdown amount labelled "filters" one is not sure that this is not simply the items purchased from filter manufacturers such as the bottom material, the medium, the surface wash equipment, the throughs, etc. and leaves out the filter basin itself and the pipe gallery. The complete lack of standardization in the available data makes it far less than satisfactory for purposes of the analysis attempted. The proper way to undertake such an investigation would be to prepare detailed cost estimates in which the equipment items are specifically segregated.

Nevertheless in order to extract as much information as possible from the selected data, and to plant some guide posts for further investigation, the following analyses are made.

In some cases it was possible to separate out the raw water pump station and that portion of the treatment plant which could be called the finished water pump station. In most cases the latter is integral with the treatment plant itself and housed in the same

building. The available data, shown in Table 22 have in some cases been adjusted to prorate total building costs to the area occupied by the finished water pumping equipment.

TABLE 22
RAW WATER AND FINISHED WATER
PUMP STATION CONTRIBUTIONS

Plant No.	Size	% contribution RW	Plant	FW
2	large	14.4	73.8	11.8
7	small	4.9	90.2	4.9
13	large	5.3	85.0	9.7
14	small	9.6	62.1	28.3
15	large	5.0		
18	small	2.0	86.4	11.6
19	large	3.8	58.4	37.8
29	"	17.0	77.2	5.8
Median		6.5	79	12.5
σ ratio		2.5	1.2	2.6

There is no difference between large plants and small plants. But as may be seen there is a wide range in the percentage contribution of the two pump stations, some of which of course depends on the TDH of the two installations which largely result from geographical factors. The high dispersion is indicated by the high σ ratio. The results probably should not be pressed further than to state that the treatment plant itself will represent 55-90 percent of the total cost with a median around 80% and that the remaining 20% comprises the raw water pump station and the finished water station in various proportions, in the median the finished water pump station contributing twice as much as the raw water pump station. Statistical plots of the data show that it is only the one plant in ten that can be expected to have raw water pump station contribution greater than 20% or finished water pump station contribution greater than 40%. The data also show that to a certain extent if the raw water pump station contribution is high the finished water pump station contribution tends to be low, and vice versa. Such a relation also follows logically from a random geographical placement of the treatment plant between the source and the distribution system such that whatever part of the total dynamic head is not taken up by one station must be taken up by the other.

The preceding considerations are of importance in the investigation of the effect of water quality on treatment cost since a-priori it would be expected that raw water quality can have very little influence on the cost of raw water pumping or finished water pumping.

Therefore if these two components in general made up the major part of the cost (in this case the investment cost) the possible effect of raw water quality on over-all cost would be submerged. However, these data show that in general it is the treatment plant portion itself that contributes the major part of the total investment cost.

Table 23 shows the remaining few breakdowns for individual items that could be segregated.

TABLE 23

CONTRIBUTION OF EQUIPMENT COMPONENTS

% of Total Cost

Plant No.	2	8	12	13	14	17	Average
Size	l	s	l	l	s	l	
Filters		>30	13.2	23.6	6.5		18
Filters + bldg.	43						
Building				30.2	44.4	75	44
Sedimentation basins	5.3		24.5	21.0			
Clarifiers					6.5		14

This shows that the contributions of filters, sedimentation basins, and clarifiers are comparatively small. A major item in the cost of the installation is apparently the "building" which as previously explained may include some of the structural portions of the equipment items. This table should be considered only as presenting a hint toward the investigation of the proposition that if one wishes to reduce the cost of treatment plants one should not spend too much effort trying to reduce the cost of filters, sedimentation basins and clarifiers, before he has more thoroughly investigated whether it is not possible to reduce the cost of housing the installation.

Table 24 shows the segregatable data on the cost of filters. Adjusting the point for plant No. 2 on the assumption that filters cost about 1/6th the cost of filters plus building these unit cost data show a log-log slope corresponding to about a 0.4 factor for total cost (which is on the low extreme for process equipment) and yield approximate unit costs (1964 National) of $250/sf at 100 sf, $60 at 1000 sf and $15 at 10,000 sf. The one slow sand filter studied, for which the available cost estimate has probably low order of accuracy, costs about 1/3 as much as a rapid sand filter of similar area, and incidentally about 9 times as much as a rapid sand filter of similar mgd capability.

TABLE 24

COST OF FILTERS

Plant No.	sf	$/sf (1964 National)
2	7000	186 (includes bldg.)
8	180	346
12	1800	36
13	1420	60
14	162	85
18	2760	11 (slow)

6-E EFFECT OF CLIMATE ON INVESTMENT COSTS

The preceding sections have indicated that there is some influence of climate on the equipment and type of construction for treatment plants but that the contribution of some of these types of construction and equipment influenced by climate is rather small in comparison to the total investment. Accordingly one would expect to find that the effect of climate on investment cost is not great. That this is indeed the case was demonstrated by plotting the deviation ratio of the investment (ratio of unit investment to median unit investment from the regression line at the actual capability) against the climatic measure, annual days with minimum temperature below $32^{O}F$. It was obvious from the plot, without requiring statistical computation, that there was no trend in investment deviation ratio with days below $32^{O}F$. The conclusion is that the dispersion of investment cost ascribable to the to the requirements of climate is very small compared to the dispersion in investment costs arising from other non-specified causes.

CHAPTER 7

RELATIVE CONTRIBUTION OF COST COMPONENTS

7-A CONTRIBUTION OF COST COMPONENTS, MAJOR CATEGORIES

The contributions of individual cost components in each plant are found in Table 13. To provide a general view of the contribution of cost components a computation has been made for "typical" plants in two size categories, standardized as Q_d's of 0.5 and 8.0 mgd, and at a utilization factor of 0.47 which is the median utilization factor of all plants interviewed. This computation has been made by correlating (log-log) investment, maintenance and repair, miscellaneous, heating, and design manpower with Q_d and energy and chemicals with $\bar{Q}$. The trend lines were read at 0.5 and 8.0 Q_d. The typical plant then is one which has the median value for each cost component and has a Q_d of 0.5 or 8.0. The results are shown in Table 25. (The reader is cautioned against interpreting the totals in Table 25 as median total costs such as may be read from Figure 5. It happens that a plant which has the median cost in each component has a total cost greater than the median total cost.)

TABLE 25

CONTRIBUTION OF COST COMPONENTS, TYPICAL PLANTS

¢/Kgal of $\bar{Q}$, and %

Q_d	0.5				8.0			
$\bar{U}$	0.47		1.0		0.47		1.0	
	¢/Kgal	%	¢	%	¢	%	¢	%
Investment	18.5	45.0	8.7	41.2	7.02	48.7	3.30	42.9
Manpower	15.3	37.0	7.2	34.1	3.89	27.0	1.83	23.8
Energy	3.5	86	2.9	13.7	1.85	12.8	1.51	19.6
Sub-Total		90.6		89.0		88.5		86.3
Chemicals	1.8	4.3	1.4	6.6	.89	6.2	0.71	9.2
MR	0.7	1.8	0.34	1.6	.28	1.9	0.13	1.7
Misc.	0.2	0.6	0.11	.5	.23	1.6	0.11	1.4
Heating (140day)	1.0	2.4	0.46	2.2	.23	1.6	0.11	1.4
TOTAL	41.0	100	21.1	100	14.39	100	7.70	100

It should be reiterated that these costs are those of raw water pumping as actually practiced, the treatment process itself, and finished water pumping as actually practiced, but not including the cost of the investment in raw water or finished water pipelines. Also it should be noted that the heating in the above table is about the maximum heating cost to be experienced in the United States. In the South heating costs would be zero.

It is seen that the major contribution to the total cost is made by the investment, it being of the order of 40-50% of costs depending on $\bar{U}$. The next major item is manpower contributing 27%-37% in plants at typical utilization factors. Ranking well below the first two is energy with about 8-13% contribution. The total contribution of these three major items makes up nearly 90% of the cost. Chemicals contribute 4-6% and heating and maintenance and repair each about 2%.

From these figures it is obvious that no major reductions in treatment costs especially at actual $\bar{U}$'s can be expected via the components chemicals, maintenance and repair, miscellaneous and heating. To reduce treatment costs the primary candidate for attention should be the investment and the secondary candidate manpower.

It happens that both of these major contributors, that is, unit investment and unit manpower consumption, show considerable dispersion among the interviewed plants. It is therefore of interest to consider how the costs could be changed if the typical plant in the above table could have operated in investment and manpower at a level which is achieved by the 10 percentile plant. The ratio of the 10 percentile investment to the median investment is 0.6 and of the 10% unit manpower cost to the median cost for small plants is 0.8 and for large plants is 0.55. (It is to be noted that the manpower figure includes both the unit consumptions and the unit prices.) Applying these factors to the corresponding components from Table 25 there results the data in Table 26.

TABLE 26

CONTRIBUTION OF COST COMPONENTS, "BEST PLANTS"

Q_d	0.5		8.0	
$\bar{U}$	0.47		0.47	
	¢/Kgal	%	¢/Kgal	%
Investment (10%)	11.1	36.1	4.21	42.18
Manpower (10%)	12.2	40.3	2.14	21.8
Energy (50%)	3.5	11.4	1.85	18.8
Subtotal		87.8		83.4
Chemicals (50%)	1.8	5.8	.89	9.1
MR "	0.7	2.3	.28	2.9
Misc. "	0.2	0.7	.23	2.3
Heating " (140 day)	1.0	3.4	.23	2.3
TOTAL	30.7	100	9.83	100
% of typical plant	75%		68%	

It is seen that even if the figures for investment and manpower are those of the 10 percentile plants yet these two items still remain the major components of total cost. These "best plants", small and large, would produce water for 75% and 68% resp. of the median plants.

Of course, major changes in technology might bring about radical reductions in investment or manpower. One particularly thinks of more widespread use of automatic plants capable of unattended operation which probably in present day technology could be achieved at an increase in investment cost less than the corresponding decrease in manpower that they might allow. But outside of such developments it does not seem reasonable to expect that plants in general could do much better in manpower efficiency than the 10 percentile plant, or be more fortunate in economical design and achievement of low bid prices than were the 10 percentile plants in that regard.

Accordingly under present technology it is unreasonable to expect cost reductions of much more than one-quarter or one-third for small and large plants resp., as compared to the present medians. This is not to say that every effort should not be expended to achieve these ideal performances. The possibility of reducing costs from 40¢ to 30¢/Kgal and from 14¢ to 10¢ is certainly worth pursuing. On the other hand the economies to be achieved by pursuing lower prices for chemicals, lower maintenance costs, or lower heating costs will not make a very big dent in the cost of water treatment.

This deduction is important enough to bear re-emphasis. Table 25 and some of the unit cost distributions may be manipulated to show what is of importance in cost reduction. If the plant has not been built it is worth a great deal of effort to obtain the lowest possible construction cost. Taking chemicals as the major cost among the minor components (the unit chemical cost is generally greater than the MR, miscellaneous and heating cost put together) one may inquire how much reduction in investment corresponds to the unit cost equivalent of reducing the unit chemicals cost to zero, which is roughly equivalent to reducing the unit cost of chemicals, MR, miscellaneous and heating by 50%. At $\bar{U} = 0.47$ if the anticipated unit investment is median for the small plants a 10% reduction in investment would produce a saving equivalent to eliminating the chemicals entirely. This corresponds to reducing the percentile level of the investment from the 50th percentile to the 43d percentile. For the large plants the equivalent reduction in median investment is 13%, corresponding to a reduction from the 50th percentile to the 37th percentile.

The preceding are the figures for a plant contemplating a median investment. However, if the plant is faced with construction costs placing the investment in the 90th percentile level then for the small plants a 4% reduction in investment would be the equivalent of eliminating the chemicals entirely, and this corresponds to a reduction from the 90th percentile to the 88th percentile. Similarly for the large plants a 7% reduction in the 90th percentile investment would be the equivalent of eliminating the chemicals and this corresponds to a reduction from the 90th to the 85th percentile. What has been said about reducing the investment, percentagewise, also applies to the possibility of reducing the interest on the financing, since the unit investment cost is the product of these two numbers.

If the plant has already been constructed the manager is saddled with the investment cost and it is outside of his sphere of responsibility from that time forward. Then similar statements not quantified here, could be made about the importance of reducing manpower as compared with reducing chemicals, maintenance, etc. since after investment manpower represents the largest unit cost.

When one considers that a reduction in the cost of chemicals, MR, or miscellaneous involves persistent ingenuity and constant attention over the entire life of the plant, some 30 years or more, whereas the reduction in investment interest rates involves ingenuity,

attention and acumen (albiet probably of a higher order) over only the period of plant design and construction, it is clear that it is a worthwhile goal to apply during the year of design and construction every possible cost reduction device. It is also clear that during this period every effort should be made to reduce unit manpower since once an excessive manpower has become established by virtue of design or tradition it is exceedingly difficult to reduce it. The question of whether extra investment expense (as for an automatic plant) is justified against the potential saving in manpower is not fully answered by the present study and a final statement on this should await the collection of additional data. It is clear however that if excessive manpower is going to be applied anyway, then there is no economic advantage in the incorporation of automatic labor saving features whether they increase the plant investment or not.

7-B CONTRIBUTION OF COST COMPONENTS - MINOR ITEMS

This Section relates certain special studies in the economics of treatment.

Water Balance In Plant — The study on water balance was undertaken to see if there were not some generalities that could be used to fix a figure for saleable water production of a plant. In particular raw water quality parameters may affect the percent recovery of saleable water from raw water and therefore the effect of quality on cost should be studied in terms of the cost of saleable water.

Figure 4 shows the plant water flow in a typical plant, illustrating some considerations to be taken in studying the water balance of plants. Before the raw water ever reaches the plant it is subject to pipeline losses and to losses in plant service at the raw water pump station. The study data do not in general take these losses into account since in most of the cases the raw water meter was located at the treatment plant as indicated by the filled-in circles signifying typical points for location of meters or computation of flows. These points do not indicate that it is typical to have such a measuring point, simply that if there is a meter or measuring point for that particular service it is likely to be located in the position located.

The first major lossess that occur are that for sludge drain or sedimentation basin cleaning. Sampling losses occur at various points along the line typically from the raw water, from the sedimentation effluent, and from the finished water. In some plants it is customary to leave the sample taps running constantly. The sample water may be wasted to the sewer or it may be returned to various points in the process. Prior to the sedimentation basin the stream has received the water used in the chemical feeders and some chemical feeder water also is applied typically to the filter effluent, to carry the chlorine. This feeder water does not represent lost water since it is recycled in the process. The filters receive of course the backwash which is lost and also the rotary surface wash or hose surface wash which typically comes from the finished water line. The finished water line also typically supplies the plant service water. It is not typical to meter this plant service water and where it is metered the plant service amount may include that for surface wash and chemical feeders. In this study the plant service designation will be restricted to that portionof such water which is actually lost to the process, i.e. in the category specified in the figure.

PLANT WATER FLOW

TYPICAL

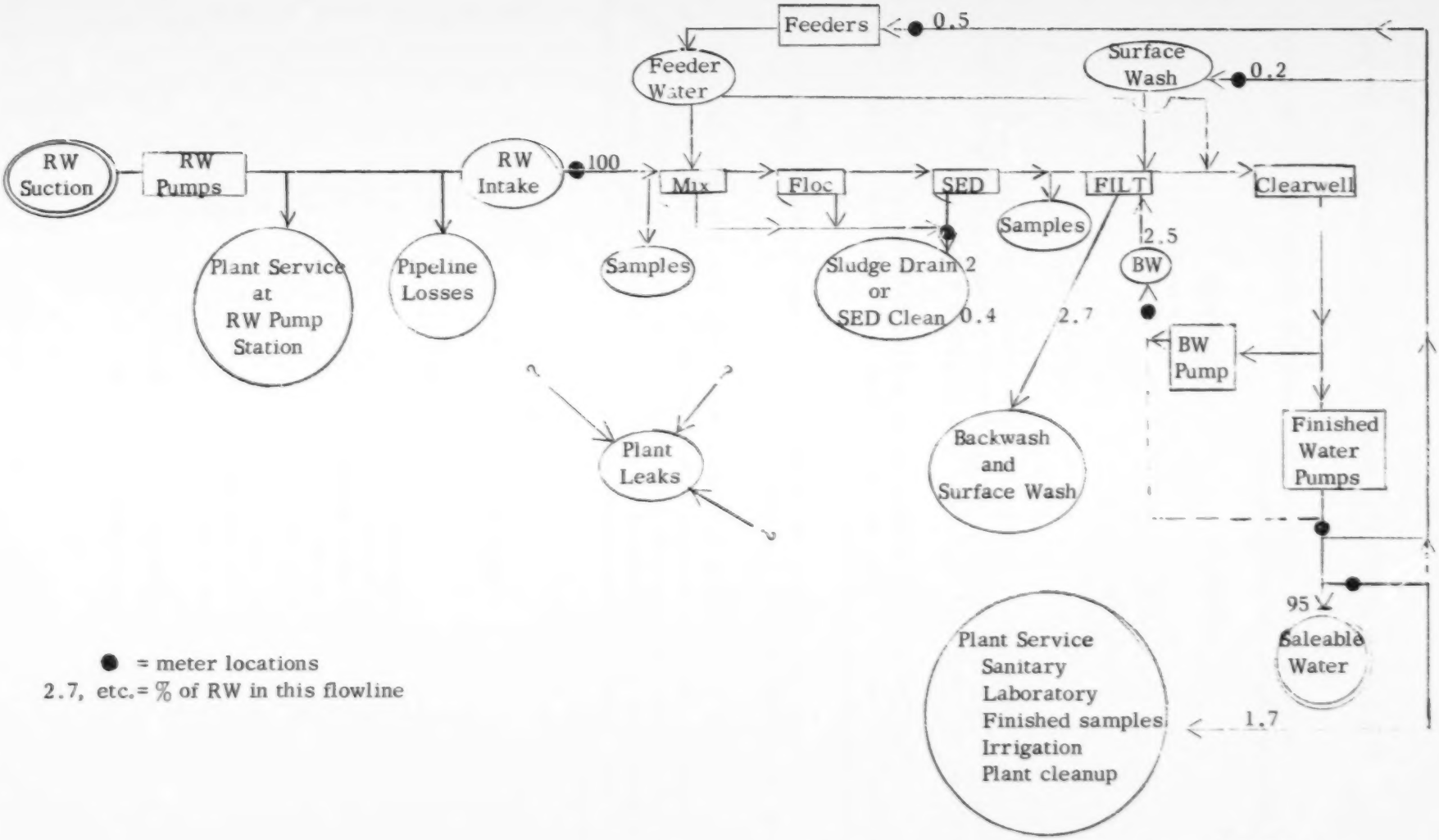


FIGURE 4

LK-R #429

The numbers on the figure indicate typical flows based on the raw water intake as 100.

Chemical feeder water was not metered in any plant but typical water flow rates for chemical feeders are as follows (7):

Chemical	gals water / lb
Alum	2
Lime	1
Carbon	1
Cl	150 (variable)

Suspended solids contact clarifiers typically lose in the sludge draining 2%. The loss in draining sedimentation basins preparatory to cleaning is about 0.4 and the loss of the actual washdown water from a fire hose only about 0.03.

Only one plant had a meter on the surface wash water. Rotary surface washer specifications call for 1/2 gpm per sq. ft. which at median rational filter runs gives a surface wash percentage of about 0.2.

In the two plants for which measurements were available plant service water, not including surface wash, average 1.7%.

This water balance is summarized in Table 27. The table also lists a computed percentage for sample taps assuming that two sample taps (in addition to the finished water tap) are allowed to run continuously at 1/2 gpm. Not all plants have this practice but if they did the loss would be about of the order of 0.01% for the large plants and 0.5% for the small ones. Also listed for completeness are the plant leaks, of which the amounts are unknown.

TABLE 27

MEDIAN PLANT WATER LOSSES

	SED	SSCC
Sludge drain	---	2
SED drain	0.4	---
SED wash (hose)	0.03	---
Backwash	2.5	2.5
Surface wash	0.1	0.1
Plant service	1.5	1.5
Sample taps (2)	0.01-0.5	0.01-0.5
Plant leaks	unknown	unknown
TOTAL	5.0-5.5	6.6-7.1
Recovery	95	93

It is seen that median recoveries of the order of 95% for sedimentation basin plants and 93% for the suspended solids contact clarifiers can be expected, less the unknown amount for plant leaks.

In none of the plants studied were there available accurate figures for raw water intake and saleable water which could be used to obtain the total losses by difference. The inaccuracies in the measuring devices were too great to expect any reasonable degree of accuracy in the small difference between two large numbers.

Most of the plants in the study did not measure the plant service water by which practice it might be assumed that plant service water is but a small percentage. However, the two plants that did measure plant service water showed the quite high percentages above indicated. There is no reason to assume that these plants were designed with meters on their plant service water with specific foreknowledge that this would be unusually high, and therefore it may be hypothesized that plant service water is of this order in many plants. If that is the case attention should be directed to it. A great deal is made of the backwash percentage, this figure being computed by practically every plant and called for by almost all State Health Department reports. Yet plant service water which represents a loss of almost equal magnitude is not even measured by most.

A table such as Table 27 showing median water losses can give an incorrect impression of security in the data. Actually figures on sludge drain were available for only one plant in the study, and for plant service water for only two plants. In only two plants were data available on the raw water intake and the saleable water production which did not show inconsistencies. It is not certain that the figures are accurate even for these two plants because of the inherent inaccuracies in metering. However, the data for these two as well as for two others are shown in Table 28.

TABLE 28

WATER BALANCE, SELECTED PLANTS,
% of Raw Water

Plant No.	4	21	13	2
SED drain	.16	.14	.18	.30
SED wash	(.03)	(.02)	(.03)	(.05)
BW	1.1	2.1	2.8	3.4
Surface wash	(.05)	.06	(.2)	(.2)
Plant service	1.7	1.3	1.0 est.	1.3 est.
Total accounted for	3.1	3.6	4.2	5.2
Unaccounted for by difference	3.9	---	0.5	---
Measured recovery	93.0	---	95.3	---
Ratio $\frac{\text{accounted for loss}}{\text{BW}}$	2.8	1.7	1.5	1.5

( ) = computed

It is seen that the losses that can be accounted for are from 1.5 to 2.8 times the backwash percentage. If the measured recovery is considered correct the unaccounted for losses are 0.5 in one plant and 3.9% in another. The basic datum for most plants was the raw water intake and since the measured recovery figure was uncertain no attempt is made in this study to compute the costs per unit of saleable water.

The Cost of Backwashing

The cost of backwashing is composed of the cost of manpower, the cost of energy, and the cost of water used in backwashing. The typical costs of these can be computed from rational filter run, backwash percent, backwash energy consumption, electric energy price, labor price, and size of filters; and the backwash cost as a percent of total cost can then be computed given total cost. The computations have been carrried out using as basic data the median values of the distributions and also the values of the worst 10%. The results are shown in Table 29. For the computations it has been assumed that one backwashing requires 10 minutes of operator time. Actually the incremental cost of labor for backwashing is zero because the operator is paid the same amount regardless of whether he is engaged in backwashing or not. In other words less backwashing would not reduce the total labor costs nor would more backwashing increase them.

TABLE 29

COST OF BACKWASHING

	Small		Large	
	median	worst 10%	median	worst 10%
Manpower, ¢/Kgal RW	.0615	.247	.0210	.097
Energy, "	.0148	.107	.0092	.062
Water, "	.707	3.58	.248	.891
TOTAL, "	.783	3.93	.278	1.050
Water cost, % of BW cost	90.0	91.4	89.4	84.5
BW cost, % of total cost	2.44	5.16	2.48	5.55

It is seen that the major cost of backwashing is the cost of water used in backwashing. This amounts to about 90% of the total cost of backwashing. In the computation the cost of water used in backwashing has been taken as the total cost of water sold. The actual cost of the water used for backwashing is somewhat less than this because usually the water used for backwashing has not had expended upon it the energy for finished water pumping which typically represents something of the order of 5% of total cost. Thus the true cost of water used in backwashing is about 5% less than shown in the table but this has been neglected in the present computation.

Since backwash water cost is about 90% of backwashing cost the backwashing cost as a percent of total cost (of raw water) may be approximated by multiplying the backwash percentage by 1.1.

It is of interest to apply these computations to the economics of long filter runs. At the median rational filter run of 4.75 Kgal/sf backwashed and the median backwash percentage of 2.21 the amount of backwash water used is 105 gallons/sf, or a median backwash

time at 15 gpm/sf of 7.0 minutes. This figure corresponds well with typical data on backwashing times collected during the study. Using 2 gpm/sf as a standard filter rate and using the 1.1 factor mentioned in previous paragraphs, the following relation may be shown to hold:

$$\text{Median backwash cost as percent of total cost} = \frac{96}{\text{hrs. filter run}}$$

Table 30 shows some pertinent computations from this relation.

TABLE 30

ECONOMICS OF LONG FILTER RUNS

Hours run	BW cost, % of total (median) cost	BW cost, ¢/Kgal	
		@ 15¢ water cost	@ 40¢ water cost
10	9.6	1.44	3.84
20	4.8	.72	1.92
40	2.4	.36	.96
60	1.6	.24	.64
80	1.2	.18	.48
100	0.96	.15	.38
120	0.80	.12	.32

From this table it may be seen that if filter runs in this median case drop from 40 hours to 10 hours the plant has experienced an increase in cost of 7.2%. But if runs increase from 80 hours to 120 hours the plant has experienced a saving of only 0.4%. In the last two columns of the table the effect is expressed in terms of ¢/Kgal at total treatment costs corresponding to large plants and small plants, resp. If filter runs drop from 40 hours to 10 hours the cost increment in large plants is 1.08¢/Kgal and in small plants 2.88¢. Therefore it is economically important to keep runs at the 40 hour level rather than the 10. However if runs are increased from 40 hours to 80 hours the saving in large plants is only about 0.2¢/Kgal and in small plants about 0.5¢. This means that it is not economically so important to have runs greatly in excess of 40 hours since the incremental saving achieved is continually diminishing. Of course if there are no other disadvantages plant management would aim for the longest possible filter runs since they do achieve a positive though small saving. However, if some other effect should enter the picture, for example if excessively long filter runs should increase the chances that coliform organisms would pass through the filters even though they have not reached the limiting loss of head then the above cost engineering analysis shows that excessively long filter runs would not be worthwhile since the economic saving achieved by them is very small.

The point of diminishing returns, at about 40 hours in the previous example, depends on the gallons per square foot used in backwash. With all else held constant the hours of diminishing returns will be less than 40 if the gpsf is less than 105 and greater than 40 if it is more than 105.

In absolute units, ¢/Kgal, the cost of backwashing is proportional to the amount of water used per backwash and to the ratio of the cost of treatment to the hours of filter run (at 2 gpm/sf). From this relation it can be seen that the ¢/Kgal cost of backwashing depends not only on the filter run achieved but also on the total cost of treatment representing the value of the water used. The higher the total treatment cost the higher will be the hours of filter run at which the point of diminishing returns is reached. This means that from the standpoint of unit costs (not percentage savings) it is more important to seek long filter runs in small plants than in large ones.

Cost of Cleaning Sedimentation Basins

The study on the cost of cleaning sedimentation basins was directed toward the economics of mechanical sludge removal. The costs for the periodic cleaning of sedimentation basin comprise the manpower and the water drained from the basins prior to cleaning and used from the fire hose during the actual cleaning. At median values of these factors the costs in large and small plants are shown in Table 31. The manpower includes both the regular plant labor and outside labor especially hired for the periodic cleanings. Of these the regular plant labor is paid whether they are cleaning sedimentation basins or not, so the only incremental manpower cost due to increased cleaning of basins is the outside labor. However, that fact is neglected in the computations. It is seen that the cost of cleaning basins is of the order of 0.1¢/Kgal of raw water. It amounts to about 0.5% of total treatment costs and the water cost is the major component being 72-91% in large and small plants resp.

TABLE 31

COST OF CLEANING SEDIMENTATION BASINS

	Large	Small
Manpower, ¢/Kgal	0.0175	0.0128
Water, "	0.0435	0.125
Total "	0.0600	0.1378
Water cost as % of total	72.5	91.0
% of total treatment cost	0.54	0.43
Mechanical sludge removal:	8.0mgd	.5 mgd
20% of 15% investment saving ¢/Kgal	- 0.175	-0.51
Water at 2.4% "	.269	.766
Energy to run equipment, "	n.a.	n.a.
Sub-total cost for mechanical removal "	+0.094	+0.256
Available to finance mechanical removal	none	none

In the lower portion of Table 31 there are shown the results of computations on the cost of mechanical sludge removal. The first item is a negative cost, or a saving, which comes about because the size of the sedimentation basin can be reduced by 20% with mechanical sludge removal. In this computation the contribution of sedimentation basins to the total investment is taken as 15%. The study did not provide any information on amount of sludge drainage from conventional sedimentations basins with

mechanical sludge removal. The computation assumes that this percentage is the same as the median percentage for suspended solids contact clarifiers. The amount of energy required to run the mechanical removal equipment is not taken into account here.

The table indicates that although there is a saving in investment cost this is more than offset by the increased cost of water used in the continuous drainage, so that the net cost of mechanical sludge removal is 0.09¢/Kgal for an 8.0 mgd plant and 0.25¢ per Kgal for a 0.5 mgd plant. If this cost were less than the cost of cleaning the conventional sedimentation basins the difference could be applied to the amortization of an investment in mechanical sludge removal equipment. However, the cost is actually more than for conventional cleaning even without the amortization of the removal equipment. If the above assumptions concerning the basic data are approximately correct it may be concluded that whatever the reason for mechanical sludge removal in conventional sedimentation basins in median plants it is not that they will save money over the costs of manual cleaning.

However, the 2.4% sludge drain is critical to this computation and if that is appreciably too high the above conclusion is not correct.

Furthermore, in this as in the other expositions in this chapter, it should be recognized that the conditions explored are the median or typical conditions. They therefore show in general what the situation is, but the proper decision for each plant can only be obtained by using the actual data for that plant.

For example when a similar computation is carried out using data from the worst 10% or 90% of the distributions so as to be most favorable to mechanical sludge removal (except that total water costs are retained at the medians since they appear in both parts of the comparison) then it is found that an investment in mechanical sludge removal would be justified up to the extent of 8% of the total investment in large plants and 4% in small plants. The cost engineering analysis shows that factors favorable to mechanical sludge removal are high unit cost of sedimentation basins, low percentage of sludge drain in the mechanical removal equipment, high labor prices, high labor utilization in sedimentation basin cleaning, high usage of water in cleaning sedimentation basins (i.e. high frequency of cleaning) and of course low cost of the mechanical removal feature. The effect that a high total cost of treatment has on favorability for mechanical sludge removal depends upon the percent of basin cleaning water as compared with the percent of sludge drain water. If the sludge drain water is higher in percentage than the basin cleaning water low total treatment costs will favor mechanical sludge removal. A plant must have the proper combination of these factors in order to justify mechanical sludge removal equipment on economic grounds.

7-C COST ESTIMATING PROCEDURE

It has been shown that investment, manpower and energy are the major contributors to the total cost of water treatment and the distribution data have shown that the variances in unit investment, unit manpower, and unit energy are high. For example, between the 10 percentile and the 90 percentile level unit manpower can vary three-fold in large plants and eight-fold in small plants. Over the same percentile range energy consumption can vary three-fold in large or small plants. This means that even if the unit

prices were the same for all plants, no estimating method based on the data from the present study could be expected to provide even approximate extimates for the costs for a particular water treatment operation. However, it is possible with a considerable degree of accuracy to estimate the average cost for a reasonable number of identical plants and therefore to estimate with reasonable accuracy the total cost of a reasonable number of plants.

Assuming that the errors due to variances in unit investment and in unit manpower and unit energy consumption have been averaged out there still remain a number of parameters which influence the costs of treatment. Among these are the temporal and regional price levels which can be adjusted by suitable cost indexes. Other such parameters are the unit prices for energy and manpower, which also can be allowed for in some degree by means of indexes.

At the expense of considerable computational effort the reader may introduce variations in the basic parameters and attempt to adjust estimated costs in accordance with the details of any set of parameters. As an example Table 17 shows that median unit consumption of manpower in large plants is 10.5 man hours/mg, while Table 15 shows that the median unit price of operator and maintenance labor in large plants is 2.40 $/hr. Roughly one would expect that the unit cost of manpower (largely made up of operator and maintenance labor) in large plants would be 2.40 x 10.5 or 25.2 $/mg. Table 19 shows indeed that the median unit cost for manpower in large plants is 22.0 $/mg. If the reader wishes to estimate for a high labor price region where unit prices were say 3.75 $/hr he could expect that unit costs would be approximately

$$22.0 \times \frac{3.75}{2.4} = 34.3 \text{ \$/mg}$$

However, manipulation of such figures is not readily done by one not completely familiar with the ramifications of the data. In order to provide an estimating procedure for total costs there is presented Figure 5 which provides for variations in Q_d and $\bar{U}$, utilization factor, and also provides means for estimating total costs at various percentile levels at combinations of these two parameters. This figure has been compiled by computing for each plant the total cost at $\bar{U} = 0.2$, 0.5 and 1.0. Regression lines were then computed for unit total costs versus $\bar{Q}$ at each $\bar{U}$ value, and it is these regression lines which comprise the estimating lines at $\bar{U} = 0.2$, 0.5, and 1.0 on Figure 5.

The means of adjusting actual unit component costs of plants operating at various $\bar{U}$'s to a $\bar{U}$ of 1.0 has been explained in Chapter 2-D-5 on unit costs. The adjustment of individual plant component costs to $\bar{U}$'s of 0.2 and 0.5 proceeded from the same assumptions but the assumption concerning manpower must be elaborated. For plants which operated and were attended 24 hours a day, and for automatic plants capable of unattended operation the daily manpower is taken as constant, that is independent of $\bar{U}$ and of daily hours of operation. A number of the small plants operated less than 24 hours per day and were not capable of unattended operation but were attended only during the hours of operation. For such small plants it was taken that if the $\bar{U}$ were to be adjusted upward this would first be accomplished by raising the production filter rate to the design filter rate or to that filter rate which would produce the adjusted $\bar{U}$. If the adjustment up to the design filter rate did not accomplish the desire $\bar{U}$ then the hours of operation, that is the manpower would be adjusted upward to reach the adjusted $\bar{U}$ at the design filter rate. If the actual $\bar{U}$ were to be adjusted downward, it was taken that this would be accomplished by reducing hours of operation, that is manpower, while maintaining the actual filter rate. The statistical characteristics of the three regression lines are shown in Table 32.

The σ ratios for these regression lines are significantly lower than the σ ratios for the individual component costs. This indicates that the association of individual cost components with each other is not random but that there is some tendency for high costs in some components to be associated with low costs in others so that the dispersion in total costs is actually less than the dispersion in costs of any individual components. As a practical matter this means that if one does not wish to adjust individual components to fit particular circumstances then one may achieve a smaller error of estimate by estimating total costs than in estimating individual component costs.

The last two rows in Table 32 provide the data whereby total costs may be estimated from Figure 5 for any percentile level of the distribution. Figure 5 shows the total costs for the median plant in the distribution. If one wishes to know however what the total cost might be for the 90 percentile or the 10 percentile he multiplies the median cost by the deviation ratio for the 90 percentile or the deviation ratio for the 10 percentile. The σ ratios and the two indicated deviation ratios increase slightly in passing from $\bar{U} = 1.0$ to $\bar{U} = 0.2$ for a technical reason not explained here. The difference is small however and no more than a $\pm$ 7% error (at 90 percentile and 10 percentile) will be introduced by taking the σ ratios and deviation ratios at all $\bar{U}$'s as being the same as those at $\bar{U} = 0.5$.

TABLE 32

CHARACTERISTICS OF REGRESSION LINES FOR TOTAL COSTS

$\bar{U}$	0.2	0.5	1.0
Number of points	19	19	19
Correlation coefficient	.664	.835	.907
σ ratio	1.39	1.31	1.24
Deviation ratio for 90 percentile	1.50	1.42	1.32
" " " 10 "	.67	.70	.76

Thus for a simple rule the cost of the 90 percentile plant at any $\bar{Q}$ and $\bar{U}$ read from Figure 5 may be approximated within that degree of approximation by multiplying the median cost by 1.42, 80% of the plants will lie between 0.70 and 1.42 x the median cost, etc.

Finally the reader should recognize that since both Q_d lines and $\bar{U}$ lines are drawn on Figure 5 it is possible for him to precisely place the position of any $\bar{U}$ line, it being the line passing through points of constant $\bar{Q}/Q_d$ ratio.

Figure 5 is to be used directly in predicting the median or most probable cost of treatment. However, if one wishes to use the predicted costs for projecting the total investment in a number of water treatment plants as in water resource planning for a region then one uses not the median but the arithmetic mean. The ratio of the arithmetic mean to the median for the data from which Figure 5 is drawn is approximately 1.04, a figure so close to 1.0 that the correction need not be applied.

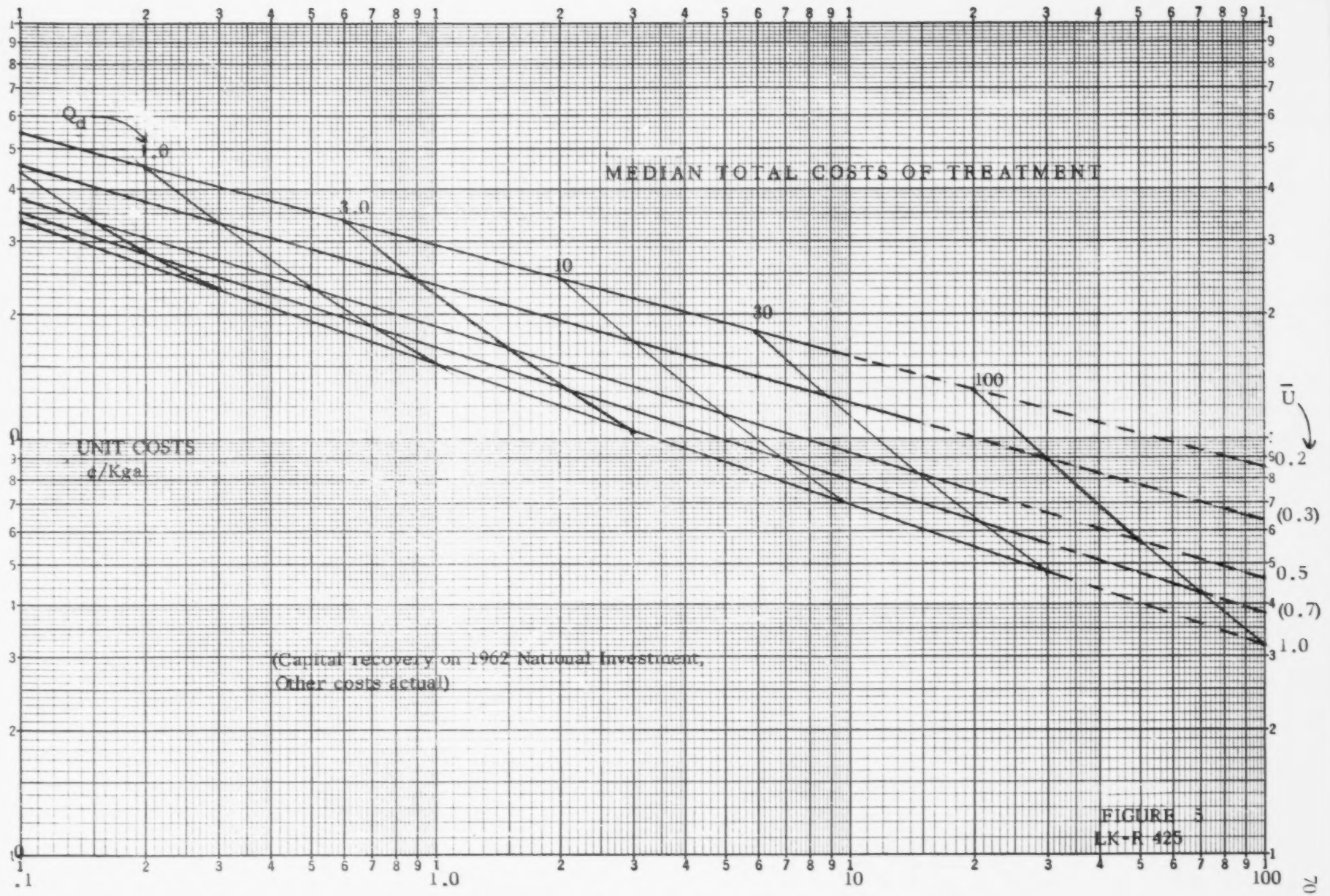


FIGURE 5
LK-R-425

CHAPTER 8

EFFECT OF RAW WATER QUALITY

It is planned to use multi-variate regression analysis under the SLURP Program on an IBM 7090 Computer in order to determine statistically the influence of the various raw water quality parameters on elements of cost and also to determine the inter-relationships among some of the non-cost operating ratios. As an example of the latter it is intended to study the effect on rational filter run of raw water turbidity and other characteristics, temperature, and sedimentation detention. These correlations are to be run in two series, one containing the monthly data and the other containing the period average data. Period average data will be used for example to explore the effect of the independent parameter on investment cost.

CHAPTER 9

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LOGBOOK REFERENCES

The work covered in this report is contained in a series of 30 interview check lists, 30 tabulations of period average and monthly data, correspondence files, and LK-R Project Logbooks No. 69, 73, and 74.

APPENDIX I

CHECK LIST

Int. No._____Page____of____
Interviewer_____
Date_____

WATER TREATMENT FACILITIES & INVESTMENT

Water Treatment Plant Description

City or Owner_____ _____

Name of Plant_____ _____

Mail address_____ _____

Interviewee_____ _____

Phone_____ _____

Capability

Past, present and future development states

Year	Rated plant capacity on filters	Rated plant capacity on pumps
_____	_____	_____
_____	_____	_____
_____	_____	_____

Life of the plant

Year worn out or obsolete _____

Design Year

Future year for which the plant is designed _____
Number of years for which this plant is designed_____

Average Flow

Average flow at beginning of plant's use, $\bar{Q}$ _____
Present average flow, $\bar{Q}$ 196___

Nearest Upstream Network Station _____

Design Engineer: Name_____ _____

Address_____ _____

Design date _____ _____

S.H.D. Office Guiding _____

S.H.D. Man Guiding _____

Title _____ Phone _____

Address _____

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INTAKE LINE

Code_____

Q_d, Q_r		
Diam		
Length		
Cost		
Yr. Const.		

INSTRUMENTATION

A_____

B_____

C_____

Code			
Cost			
Year			

PRESEDIMENTATION

A_____

B_____

C_____

Code		
Q_d, Q_r		
Detention		
Volume		
Dimensions*		
Cost sludge removal		
Cost complete		

*transverse, parallel height, i.d.

INTAKE

Cost_____

Year Const._____

LOW LIFT PUMPS

Number_____

A_____

B_____

C_____

D_____

				Total
Code				
Q_d, Q_r				
HP				
Head Static				
Head TDH				
Cost strainer				
Cost suction well				
Cost pump & drive				
Station (incl. Pump)				
Station + elec. substation				
Year constr.				

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CHEMICAL STORAGE, FEEDING, MIXING

Storage	Feeding
A_____	A_____
B_____	B_____
C_____	C_____

Material	Alum		Lime	Soda ash	C	Cl	Post Cl	
Code (storage)								
No.								
Capacity								
Cost								
Year								
Code (feeder)								
Model								
No.								
Design rate								
Application point								
Cost								
Year								
Code (mixer)								
No.								
Design rate								
Cost								
Year								
Cost of all Three								
Cost ÷ building								

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FLOCCULATION

A_____

B_____

C_____

Code			
Q_d, Q_r			
Detention			
Volume			
Dimensions			
Cost			
Year			

SEDIMENTATION

Number basins_____

Code			
Q_d, Q_r			
Detention			
Volume			
Dimensions			
Sludge rem.			
Cost			

LAND, FENCES

	Intake Pump sta.	Plant + Hilift
Acres		
Cost		
Year		

	Intake Pump sta.	Plant + Hilift
Feet fence		
Cost		
Year		

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FILTERS

A_____

B_____

C_____

Code			
Q_d, Q_r			
Dimensions			
Area			
Gravel, In.			
Sand, In.			
Media, In.			
Control hyd. or man.			
Flow Controller			
Mfgr			
Cost			
Year			

CLEAR WELL

A_____

B_____

Code	
Location	
Dimensions	
Vol. mg	
Days of Q_r	
Cost	
Year	

PIPELINE TO SYSTEM

Materials_____

Terminus_____

Code	
Ft.	
Diam	
Cost	
Year	

BW STORAGE
Ground, elevated, none

Location_____

Material_____

Capacity_____

Cost_____

Year_____

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HIGH LIFT AND BW

A_____

B_____

C_____

Treatment only?_____ Treatment & Distribution?_____

Code	BW					
Q_r						
At TDH						
Head static						
Head TDH						
Cost, pump						
Cost, station						
Cost, + elec. sub.						
Year						

OFFICES AND LAB n.e. incl.

Sq. ft._____

Persons using_____

Treatment pers. using_____

Cost building_____

Cost equipment_____

Year_____

ELEC. SUB STATIONS n.e. incl.

Purpose_____

KV_____

KVA_____

Cost_____

Year_____

TOTAL PLANT COST

A. Contract construction

B. Own labor and materials

C. Land

D. Superv., adm., & oh on constr.

E. Interest during constr.

F. Landscaping, fences, etc.

Codes_____ _____

Cost_____ _____

Year_____ _____

* * * * * *

_____

_____

_____

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WATER TREATMENT OPERATING COSTS

Period_____to_____

Accounting periods_____weekly _____monthly _____quarterly _____annual

Operating records maintained _____none _____daily _____weekly _____monthly _____annual

Lab records maintained? _____ _____ _____ _____ _____

Record copies filed with_____

Annual operating reports prepared _____yes _____no Financial reports____yes ____no

Monthly operating reports prepared _____yes _____no Financial reports____yes ____no

FY closes_____

PRODUCTION _____hrs per day average

Total for period_____ Average mgd_____

Max. day _____ Min. day_____

PERSONNEL

	Code Note	No. on Payroll	Man Hours	Total Costs	Hourly Rate	@ 24 hr/day	
Supervisor							
Operators							
Treatment operators							
Pump station "							
Maint. & repair							
MR treatment							
MR pump station							
General laborers							
Laboratory							
Clerical							
Total							
Payroll extras							

Note Codes:
A. O.M.R. personnel undifferentiated
B. Treatment operators and pump station operators undifferentiated
C. MR treatment plant not differentiated from MR pump station
D. General laborers included with this row
E. Clerical services source, distribution and/or billing function also

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Criterion for BW:

1. △ P reaches_____ft.
2. Fixed number of hours run_____
3. Number of elapsed hours_____
4. Can't maintain production i.e. loosing level in clear well_____

BW Data:

Filters washed by halves?_____yes_____no

Kgal water used____per filter____per half filter____Kgal nominal____ measured____

BW rate_____gpm_____inches per min.

BW time_____min estimated_____timed with watch_____

Surface wash: with jets_____ with hose_____ not done_____

Parameters which affect filter runs: (Supt. or operators experience or opinions)

Temp_____

Season of year_____

Turbidity_____

Alum dosage_____

CLEANING TANKS

	Mixing	Flocculation	Sedimentation
Times per year	_____	_____	_____
Man hours each cleaning	_____	_____	_____
How cleaned	_____	_____	_____

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RAW WATER QUALITY PARAMETERS

Temp (^{o}F)				
pH				
Cl demand (mgpl)				
free CO_2				
Alkalinity total (mgpl)				
Alkalinity phenol (mgpl)				
Hardness (mgpl)				
Color (scale units)				
Turbidity (scale units)				
TDS (mgpl)				
Algae, total K/ml				

ENERGY

	Unit	Total Cost, $	Unit Cost	Unit Price
Gas	Mcf			
Oil	gals			
Electricity	KWH			

Code: A - Heating B - Power for Pumping Treatment C - Power for Pumping low lift
D - Power for hi-lift E - Air conditioning, lighting, misc.

CHEMICALS

Code:
1. Cl lbs
2. Alum (17 % Al_2O_3) lbs
3. Liquid alum
4. Sod. Aluminate
5. Soda ash
6. Lime
7. Lime, recalcined
8. Carbon
9. Water
10. $KMnO_4$
11. Clay

Code							
Unit							
Consp							
Unit Price							
Total Cost							
Unit Cost							
Unit Consp							

Misc. costs

Transportation
Insurance
Taxes
MR

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DOSAGES:

What sets the dosages? (i.e. how does operator determine what dosage to use)

	Alum	Iron	Pre Lime or SA	Pre Cl	Post Cl	Post Lime or SA	C
Jar test how often?							
Floc condition?							
Fixed, conventional							
Cl res, where?							
pH, where?							
Turbidity							
Season							
Color							
Taste & odor quantitative							
qualitative							

How are dosages measured? (i.e. how does operator actually measure the dosage being used?)

Machine checked by grams per minute how often?							
Machine setting and calibration curve							
Lbs or bags put in hoppers, or cylinder wts.							

What makes for high dosages? (supt. or operator's opinions)

	Alum or Fe	Lime or SA	Cl	C
Turbidity				
Temp.				
Rain				
Season				
Color				

* * * * *

APPENDIX II

ALPHABETIC CODE FOR EQUIPMENT AND PROCESSING

Q Source
- Ql lake or reservoir
- Qr river
- Qw wells
- Qs reservoir (> 20 day detention at $\bar{Q}$)

P Pumps
- Pl low-lift
- Pp high-lift

C Chemical dosage for coagulation
- Ca alum
- Cc NaOH
- Ci iron salts
- Cl lime
- Cs soda ash
- Ct activated silica
- Co other coagulant

D Disinfection
- Dg chlorine gas
- Dx chlorine dioxide

T Chemical taste and odor control
- Tc activated carbon
- Td chlorine dioxide
- Tm $KMnO_4$

M Mixing device or tank
- Mb baffle mix
- Me turbulence of influent
- Ml in raw water line
- Mp slow mechanical mix
- Mt rapid mechanical mix

G Flocculation basin
- Gb baffled
- Gp slow mechanical

S Sedimentation
- Sb basins, baffled (other than inlet or outlet)
- Sc covered basins (other than housed)
- Sh housed
- Sm mechanical sludge removal
- Sp plain
- Sv upflow cylindrical tanks

(MTPS SV) - suspended solids contact clarifiers

R Recarbonation

F Filters
- Fa anthrafilt
- Fg gravity (slow)
- Fk covered
- Fo open
- Fr gravity (rapid)
- Fs sand

B Backwash
- Ba automatic
- Bl from high-line
- Bp with pump (direct or via storage)

V Fluoride adjustment
- Va hydrofluosilicic acid
- Vs sodium silicofluoride
- Vt sodium fluoride

APPENDIX III

SYMBOLS, ABBREVIATIONS, DEFINITIONS

Symbols and Abbreviations

FW	Finished Water
gpd	Gallons per day
gpm	Gallons per minute
HP	Horsepower
Kcf	Thousands of cubic feet
Kgal	Kilogallons
KWH	Kilowatt hours
mg	Million gallons
mgd	Million gallons per day
MR	Maintenance repair and replacement
MRR	Maintenance repair and replacement
LPG	Liquified petroleum gas
$\overline{Q}$	Average production, average raw water intake, mgd
Q_d	Design capability for raw water, mgd
RW	Raw water
sf	Square feet
σ	Standard deviation of a set of data
SSCC	Suspended solids contact clarifier
TDH	Total dynamic head
$\overline{U}$	Utilization factor $\overline{Q}/Q_d$, fraction

Definitions

Clarifier: A suspended solids contact clarifier.

Correlation coeffieient: A measure of the degree to which dispersion (variance) is removed from raw data by the correlation.

Deviation ratio: Ratio between the value of a particular data point and the value of the median or the regression line with which it is associated.

Deviation ratio of the 90th percentile: Ratio of the value of the 90th percentile of the distribution to the median value.

Firm wire HP: The wire horsepower corresponding to the maximum water horsepower that a pumping station can be guaranteed to deliver 100% of the time - that is, with the largest single piece of equipment out of service.

Installed wire horsepower: The wire horsepower capability of all the installed pumping equipment.

Percentile level: The percentage on the distribution curve of all data points corresponding to the value of the parameter in question.

σ ratio: The deviation ratio of the value one standard deviation removed from the median, or one standard error of estimate removed from the regression line.

Standard deviation in log units: The standard deviation computed from a set of data which has been transformed into the logarithms of the data

Water quality parameters: The characteristics of the raw water measured by individual concentrations of its components, its temperature, etc.

Water horsepower: Energy in the water discharge from the pump.

Wire horsepower: Electrical energy delivered to the plant meter.

Wire-to-water efficiency: Water horsepower delivered divided by wire horsepower consumed.

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